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EXPANDED KILL CHAIN ANALYSIS OF MANNED-UNMANNED TEAMING FOR FUTURE STRIKE OPERATIONS

by

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ABSTRACT

This study explores the concept of manned-unmanned teaming in the context of the joint capability areas and investigates the expanded kill chain for a manned and unmanned team for future strike operations. The study first elucidated capabilities that can be realized by manned-unmanned teams. A design reference mission for a manned-unmanned team (strike) operation was developed, enabling operational activity and functional analysis of the expanded kill chain. Simulation models were built to examine the time-efficiencies of the manned-unmanned teaming concept. This research used insights from the results of the models to explore alternatives in asset generation and systems link-up tactics. The analysis of strike operations cycle times that include total mission operations time, airborne time, and time to complete systems link-up provided data to generate recommendations. Besides identifying areas on which to focus efficiency improvement efforts, this study also proposes tactics and concept of operations to enhance the effectiveness of strike operations by manned-unmanned teams. This study reveals that fighter endurance is a limiting factor in manned-unmanned operations and proposes a synchronized launch or pre-launch establishment of communications and datalink as possible ways to mitigate these limiting factors.

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List of Acronyms and Abbreviations

A2AD anti-access/area denial

ADIZ air defense identification zone

AF2T2EA anticipate, find, fix, track, target, engage and assess

AG air-to-ground

ASCM anti-ship cruise missile

ATOL auto take-off and landing

C2 command and control

CEP circular error probable

CNO Chief of Naval Operations

COI contacts of interest

CONOPS concept of operations

COMINT communications intelligence

CSG carrier strike group

CVEX next-generation escort carrier

CVEX 2 evolution of next-generation escort carrier

DARPA Defense Advanced Research Project Agency

DCA defensive counter air

DEAD destruction of enemy air defense

DOD Department of Defense

DRM design reference mission

EA electronic attack

EEZ exclusive economic zone

EFFBD enhanced functional flow block diagram

ELINT electronic intelligence

EMCON emissions control

EOR end-of-runway

EOTS electro-optic targeting system

EW electronic warfare

F2T2E find, fix, track, target, engage

F2T2EA find, fix, track, target, engage and assess

F3EA find, fix, finish, exploit, analyze

GPS Global Positioning System

HADR humanitarian assistance and disaster relief

HARM high-speed anti-radiation missile

H-Hour The specific hour on a specific dat at which a particular operation commences.

HQ headquarters

INS inertia navigation system

IRST infrared search and track

ISAF International Security Assistance Force

ISR intelligence, surveillance and reconnaissance

JCA joint capability areas

JDAM	joint direct attack munition
JSF	Joint Strike Fighter
KCAT	kill chain analysis tool
LPI	low probability of intercept
MOE	measure of effectiveness
MS	maritime surveillance
MSR	mission success rate
MTX	missile-truck concept
MUM-T	manned-unmanned teaming
nm	nautical miles
OCA	offensive counter air
RDN	rapidly deployable network
RV	rendezvous
RWR	radar warning receiver
SAM	surface-to-air missile
SAR	search and rescue
SDB	small diameter bomb
SEAD	suppression of enemy air defense
SLOC	sea lines of communications
SOJ	stand-off jammer
SoS	system of systems

SPJ support jammer

T3 transnational terrorist threat

TTP tactics, techniques and procedure

UAV unmanned aerial vehicle

UCAV unmanned combat aerial vehicle

UCLASS unmanned carrier-launch airborne surveillance and strike

U.S. United States

USAF United States Air Force

USFOR-A U.S. Forces-Afghanistan

USMC United States Marine Corp

VLO very low observable

VTOL vertical take-off and landing

Executive Summary

Traditionally, reconnaissance missions used unmanned aerial vehicles (UAVs). In recent operations, UAVs have been used for dedicated strike operations against surface targets. Recent advances made in swarming UAVs present the opportunities to integrate a swarming UAV system with manned fighters to realize capabilities that traditionally were realized by manned aircraft. A network of UAVs having an organic capability to self-organize and collaborate through information sharing and collective sense-making to achieve a common objective is called a swarm UAV network. The teaming of manned and unmanned aircraft could be a disruptive technology in future combat.

This study identified the capabilities realized by a swarming UAV system teamed with manned aircraft based on the joint capability areas framework. These capabilities were mapped back to the framework, ensuring that the identified capabilities are relevant to the current capability requirements. The manned-unmanned teaming for a surface strike mission was among the potential capabilities identified for further investigation. A design reference mission for a strategic surface strike executed by a manned-unmanned strike package was developed. The design reference mission included a description of the scenario, an elaboration on the threats and analysis and mapping of the operational activities and functions.

A kill chain is a sequence of activities, that when executed successfully in the prescribed sequence, leads to the destruction of an objective or target. Traditionally, the kill chain only specifies the final phases of target location, identification, designation and engagement. In this study, an expanded kill chain was developed to include asset generation, manned and unmanned communications establishment (link-up) and the ingress and egress processes. The basic kill chain and the expanded kill chain are then modeled using Imagine That Inc.'s ExtendSim 9.0, a discrete event simulation software. ExtendSim enables the modeling of simulation items that are generated and processed by discrete activities as the items travel through the model along a defined path. Activity blocks along the path simulate the performance of service or impose delays on the items. Researchers assign attributes to each simulation item to facilitate the understanding of the behavior and traits of the item as it moves through the model.

Measures of effectiveness are selected to assess the limiting factors of the expanded kill chain. The measures of effectiveness are Total Mission Time, Mission Time and rendezvous time. Total Mission Time measures the time from the beginning of asset generation to the time the strike package completes the return to the launch platforms. Mission time measures the total time the assets are airborne. Rendezvous time measures the time it takes for the strike package to form up. In this study, a manned-unmanned teaming strike package is defined as a flight of four manned fighters and eight unmanned combat aerial vehicles. For the basic kill chain, mission success rate, defined as the percentage of targets destroyed, is identified as the single measure of effectiveness.

For the basic kill chain model, analysis is focused on the main effects from the probabilities of success for the respective kill chain processes. The analysis found that whilst the probability of hit and probability of kill had some effect on the mission success rate, the probability of a correct target solution had the largest effect on the mission success rate.

For the expanded kill chain model, analysis is focused on identifying the main effects from the various processes in the expanded kill chain. The results from the expanded kill chain model suggests that the limiting factor in a manned-unmanned teaming strike package lies in the airborne formation of the strike package. From the simulation, a significant amount of time is spent either by the fighter or by the unmanned combat aerial vehicle holding at the rendezvous point. In the simulation, there is no attempt to synchronize the generation of the manned and unmanned aircraft. As a result, if a manned aircraft reaches the rendezvous point first and there are no unmanned aircraft for it to perform the link-up, the result is that the manned aircraft has to hold at the rendezvous point and wait for the arrival of the unmanned aircraft. This unsynchronized arrival at the rendezvous points creates inefficiencies and also results in precious airborne time wasted. The study then proposes three alternatives that aim either to extend the endurance of the manned fighters or to minimize the Mission Time through synchronization or changes in the activity sequence in the expanded kill chain.

The three alternatives include the use of aerial refueling tankers to extend the endurance of the manned fighters, the deliberate synchronization of aircraft launches to enable the realization of “just-in-time” arrival of aircraft at the rendezvous point, and the establishment of communications link-up between manned and unmanned aircraft prior to launch.

Analysis of all alternatives is performed to gain insights into the effects each had on the Mission Time and rendezvous (RV) Time. Benefits and challenges of each alternative are also detailed. Finally, the Pugh method, utilizing the Pugh matrix, is used to determine which of the alternative amongst the three is most suitable. The analysis of alternatives reveals that while the synchronization of aircraft launches results in a significant reduction in RV Times, it still necessitates a operations time that is longer than the manned fighter's endurance. Consequently, for this alternative, the requirement for aerial refueling is still required. On the other hand, performing the communications link-up between manned and unmanned aircraft prior to launch removed the RV Time from the calculation of Mission Time. As a result, a reduction of two hours from the original operations time was achieved, making it possible to execute the manned-unmanned teaming strike operation without the requirement of aerial refueling tankers. However, a pre-launch link-up would require stationing both launch platforms at a closer proximity due to line-of-sight communications requirements, with a consequent increase in risk to both launch platforms.

With the increasing use of UAVs in military operations, coupled with the advent of swarm technology for a network of UAVs, the teaming of manned and unmanned aircraft for surface strike missions in contested airspace presents a potential disruptive capability against any adversary. This study illuminates areas in the expanded kill chain of such a strike operation that may impact the operational effectiveness. It identifies possible tactics, concept of operations and future capabilities that will increase the operational tenability of a manned and unmanned aircraft for strike operations.

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CHAPTER 1:
Introduction

The ability to inflict damage and destruction on one's enemy remains one of the key capabilities of military operations. The employment of UAVs in military operations opens up new possibilities in strike capabilities. At present, strike operations are separated into distinct unmanned and manned aircraft operations and therein lay the possibility of teaming both manned and unmanned systems for strike operations. This study investigates the capabilities realized from this teaming and, through an analysis of the expanded kill chain of a future strike operation, identifies the potential limiting factors in the employment of the concept.

1.1 Unmanned Aerial Vehicles

Balloons were the first UAVs. They were first used in a reconnaissance role in air warfare. These balloons, launched into enemy territory, provided the forces with an advantageous "birds-eye view" over the battlefield. In his book [1], Air Marshal Joubert of the Royal Air Force spoke to the use of balloons as the first vehicles for airborne reconnaissance and balloons were first used by the Royal Air Force in military operations in Sudan in 1885 [2]. During the American Civil War and the First World War, balloons were also employed as reconnaissance platforms [3]. In the Second World War, the Japanese launched balloons loaded with explosives in their attempt to attack American infrastructures and agricultural land [4], though the effectiveness of such balloons were dismal. Despite the many attempts to employ the use of unmanned flying platforms as instruments of war, the early use of unmanned flying platforms was hampered mainly by the lack of technology for launch and control.

UAVs became more effective during the Vietnam War when the United States (U.S.) began employing them for daytime reconnaissance missions. The scope of the missions later expanded into night photography, communications intelligence (COMINT), electronic intelligence (ELINT), propaganda, target drones, and the detection, identification and location of surface-to-air missiles (SAMs).

Since then, the use of unmanned aerial systems have evolved and expanded rapidly over the past decade. While the primary role of UAVs has traditionally been in intelligence, surveillance and reconnaissance (ISR), the use of unmanned aerial systems in other domains is growing vis-a-vis the capability growth of UAVs. The "Initial Capabilities Document for Unmanned Systems (Air, Ground, and Maritime)" [5] articulated the capability of unmanned systems to provide persistent relief from dull, repetitive tasks or physically challenging tasks, while providing standoff from dirty or dangerous missions. Such missions include combat air patrol and ISR flights over contested airspace.

Consequently, the roles that UAVs perform in combat are increasingly critical to combat commanders, from surveillance for the Army and ISR over hostile airspace, to precision strikes on strategic targets. With this, the multiplier effect that UAVs bring to combat has increased many folds, and UAVs are becoming a value piece of any military's force structure. Increasingly, UAVs are becoming the preferred alternative, especially for operations that are characterized as dull, dirty or dangerous [6]. UAVs were described by the Brigadier General (BG) Riftin, Chief Artillery Officer of the Israeli Defence Force, speaking to the broad use of UAVs during the 2014 Israeli combat operations in Gaza [7], as "phenomenal" and "a real asset" that "boosted combat effectiveness of Operation Protective Edge."

The increasing value that UAVs bring to the combat operations provides the impetus to explore new and innovative ways in their employment. This study builds on the current and project capabilities of UAVs to explore the new ways in which UAVs can be employed in combat.

1.2 Kill Chains

A combat kill chain describes a systematic process to locate, target and engage an adversary to create desired effects. It is an integrated, end-to-end process described as a "chain" because any one deficiency will interrupt the entire process. First introduced by the Air Force Chief of Staff, General (Gen.) Fogleman, in 1996 [8], the United States Air Force (USAF) kill chain has evolved from Gen. Fogleman's "find, fix, track and engage" into a more encompassing kill chain to include the processes of "find, fix, track, target, engage and assess." Gen. Fogleman had used it to frame the future capabilities of the Air Force [8]. In the past decade the kill chain processes of "find, fix, track, target, engage and

assess (F2T2EA)" had been expanded to include the intelligence generation processes to form the "anticipate, find, fix, track, target, engage and assess (AF2T2EA)" kill chain.

Gen. Greenert, Chief of Naval Operations (CNO), in 2013, spoke on the use of a modified version of the kill chain to prioritize capability re-captilization. In his speech, he stated that kill chain analysis allows the shortening of the sensor-shooter loop in combat so that assets can be used more effectively to persecute targets and achieve campaign objectives [9]. Kill chain analysis have also been applied to countering cyber threats. At its most fundamental concept, the kill chain can be used to describe any sequence of end-to-end events, such that upon the completion of all events sequentially, the desired effects are achieved [9].

General McChrystal, in his essay based on his experiences and lessons from his assignment as Commander, International Security Assistance Force (ISAF) and U.S. Forces-Afghanistan (USFOR-A), said that the Army had to develop its own version of a kill chain, "find, fix, finish, exploit, analyze (F3EA)," when faced with the emerging threats of an enemy that uses twenty-first century technology. He gave the example of the Al Qaeda in Iraq evolving into a resilient and flexible enemy, and the urgent need for the Army to develop a new way to counter this emergent threat. [10]

Lieutenant General Michael of the United States Marine Corp (USMC) spoke to the USMC kill chain in his annual program review brief [11]. He identified the five processes of the USMC precision strike kill chain as "find, fix, target, track, engage" (F2T2E). In his brief [11], he identified command and control as the key enabler to improving the precision strike kill chain. He explained that the trend towards the use of UAVs operating within the kill chain demonstrates the critical need for a robust command and control network.

Despite the reference to kill chains in all services, kill chain analysis amongst the services had focused on examining the BLUEFORCE targeting and engagement kill chain to determine areas of improvement or capability development to the chain. Opportunities exist to analyze the expanded kill chain. An expanded kill chain looks beyond the activities of the kill chain and includes the per-requisite activities that lead up to the kill chain execution as well as the activities that occur after the execution of the kill chain. For example, the expanded kill chain of a F/A-18 strike operation will include the activities of mission planning and aircraft generation onboard the aircraft carrier. Insights gained from this may be

used to identify possible areas of improvements that are not illuminated by past kill chain analysis.

1.3 Kill Chain Analysis

Cheater [12], in his master's thesis, used kill chain analysis to demonstrate that the use of technologies will reduce the cycle time of the kill chain for unmanned aircraft. He highlighted the need to focus not just on the end effects of the kill chain, but also on the technologies that enable autonomy and interoperability in the war effort. Ultimately, by applying the correct technologies to the critical tasks of gathering, analyzing and distributing intelligence, an anticipatory versus a reactionary behavior towards enemy action can be achieved. Cheater had illuminated an important aspect of kill chain analysis – that while the actual actions of find, fix, track, target, engage and access are important in a kill chain, of equal importance are the prior actions that must be taken. He also cautioned that while the intent for the use of technology to accelerate the kill chain was good, the efforts could be jeopardized by political and cultural conflicts.

Bloye developed a heuristic kill chain analysis tool (KCAT) using Microsoft Excel that enables the rapid identification of capability gaps and the generation of feasible schedules that minimizes the kill chain cycle time. His study was able to demonstrate that KCAT could provide the planners and decision makers with a quantitative assessment of the value of a network-centric warfare in a time-sensitive targeting scenario. The analysis of kill chains also enabled the experimentation and assessment of future concepts and capabilities [13].

Smith [14] demonstrated that kill chain analysis can be used to analyze a ship's vulnerabilities to anti-ship cruise missiles (ASCMs). In his analysis of the kill chain framework, two approaches were used. The first approach analyzed the kill chain from a time-sequence perspective and examined the effectiveness of the ASCM for a hard kill and soft kill against the ships. The second approach used a decision tree approach to model a single ASCM against a ship's air defense system. From these approaches, Smith was able to derive the probabilities of success and failures of the missile engagements.

Wallace [15] presented a methodology for mission thread analysis, or kill chain analysis, and its application to a specific weapon target pair. He explained the importance of assessing the entire integrated systems that will provide military commanders with realistic

assessments of the system's effectiveness in the kill chain. Wallace described a mission engineering approach to kill chain analysis that assesses the system's technical capability using a specific weapon target pair in the context of a kill chain. He posited that such an approach would illuminate where capability gaps might lie as it offers the ability to assess the capability portfolio of the fleet for each mission, and the ability to drill down to each specific platform or platform class. This approach was then implemented in the warfare capability baseline study.

Given the many studies in kill chain analysis with the aim of reducing the cycle time of kill chains, it is timely that an examination of the cycle time for the expanded kill chain be conducted. To this end, insights gained from the study into expanded kill chains may be useful in helping future military planners understand the dependency of all activities and processes of a future strike operation.

1.4 The Distributed Air Wing Concept

The "Distributed Air Wing" capstone study identified a carrier/land based unmanned air-to-air fighting vehicle missile-truck concept (MTX) as a potential alternative to the realization of a distributed air wing [16]. The MTX would increase the range, payload and deception capabilities for operations in anti-access/area denial (A2AD) environments and contested airspace. The capstone study identified defensive counter air (DCA), offensive counter air (OCA) and early warning as capability areas where the MTX could close the capability gap.

The MTX concept [16] described a system of unmanned aircraft, capable of carrying air-to-air missiles. These unmanned aircraft accompany manned aircraft on fighter missions and provide persistent on-station time for offensive and defensive counter-air missions. For OCA and ISR missions, the MTX "missile-truck UAV" can be paired with a manned fighter, or controlled by an operator from the ground. The study concluded that the MTX would deliver the benefits of reducing personnel risks, increasing payload and the ability to service an increased number of targets.

Three options for the unmanned aircraft in the MTX concept were proposed by the capstone study [16]. The first involved the use of unmanned versions of existing manned fighters such as the F/A-18 Super Hornet or F-16 Falcon. An upgraded version of an existing

unmanned system such as the MQ-9 Reaper provided the second option. The third option would deliver a dedicated unmanned combat aerial system such as the developmental X-47 unmanned carrier-launch airborne surveillance and strike (UCLASS).

In a separate study, Gill [17] studied an air-to-ground strike sceanrio utilizing a pairing between manned and unmanned assets. The study compared the use of F/A-18 Super Hornets and F-35C Lightning II as the manned aircraft and found that stealth technology was a critical factor for high BLUEFORCE survivability rates. The study also concluded that a package size of four was advantageous in terms of achieving high target destruction rates.

This study takes the MTX concept and extends it to a strategic surface strike operation. Both the capstone [16] and Gill's [17] findings provide the basis for initial force structure sizing of a manned-unmanned strike package. For this study, a package consisting of four manned stealth fighters and eight unmanned aircraft will be used.

1.5 Swarms

In nature, swarms exhibit a level of intelligence and coordination significantly higher than that of an individual member of the swarm community. There had been great interest in the collaborative capabilities of such swarming communities in nature. Gordon and Greene [18] and Gordon et al. [19] found that communications between individual ants of various roles was critical to the successful swarming behavior of the colony. For example, Gordon found that an ant colony, working as a swarm community, was capable of overcoming obstacles and solving problems that was unthinkable for an individual ant. Similar swarming behaviors are observable in schools of sardines as well as in hives of bees [19].

In the realm of UAVs, Gaertner [20] defined a swarm as a network of UAVs, each UAV possessing the capability to communicate with the other UAVs within the network. Gaertner noted that the level of autonomy in the swarm was such that the network of UAVs could work together and self-organize in order to accomplish a common mission objective [20]. This network of UAVs could then be described as a swarm network. Gaertner [20] investigated swarm-versus-swarm in UAV combat tactics and identified the key factors of such engagements. His work provided tactical insights into the development of swarm tactics for future air combat scenarios involving unmanned aircraft.

A report published by the Office of the Under-Secretary of Defense for a 2009 study of time critical conventional strike from a strategic standoff highlighted the possibility of using swarm concepts as a low cost autonomous attack system against time critical targets. In such a system, the writers envisaged a swarm of weaponized miniature aerial vehicles equipped with a lasing and targeting capability that could be employed against moving or relocatable targets and are capable of multi-missile swarming tactics [21].

Muraru [22] posited the concept that UAVs operating as an autonomous system in swarming concepts can lead to improved survivability of the systems. He identified swarming as a possible area where smart coordination and cooperative technologies could be implemented through intelligent control.

The capability for unmanned aircraft to exhibit swarming behaviors can potentially enable the realization of disruptive capabilities in future strike operations. This study will utilize the insights from past studies in the exploration and formulation of potential capabilities that can be realized by the teaming of manned aircraft and unmanned aircraft with swarm capabilities.

1.6 Research Questions

The pairing of dedicated unmanned combat aerial systems with a manned fighter as a control platform presents a potential area where technologies of a swarming network of UAV can be capitalized. To this end, following are the key research questions:.

1. What are the capabilities that arise from the pairing of manned and unmanned aircraft, and specifically unmanned aircraft with swarm capabilities?
2. What is the expanded kill chain of a manned-unmanned teaming strike mission?
3. What are the potential limiting factors that preclude the employment of such a concept?

1.7 Approach and Methodology

A systems engineering approach is used to identify the capability areas where such teaming of manned and unmanned systems can be employed. Amongst the identified capability area, the design reference mission (DRM) for each capability's expanded kill chain is devel-

oped and analyzed to assess the effect that an employment of UAV system with swarming capabilities, inJoin place of manned platforms, has on the kill chain effectiveness. The main area of interest of this study is to illuminate the elements of the expanded kill chain that past kill chain analyses may not have considered. The study will make certain assumptions about the behavior and performance of the future manned and unmanned aircraft, and this thesis will document these assumptions.

1.8 Organization of Thesis

In Chapter 2, the systems engineering approach taken is first described. It is then applied to identify the possible capability gaps in current strike operations. The study then identifies the potential capabilities, based on capabilities from the Department of Defense (DOD) joint capability areas (JCA) framework that a system of swarm UAVs can realize. A mapping of the potential capabilities to the top-level JCA capabilities are shown.

Thereafter, Chapter 3 details the DRM that is developed based on the selected capability. The operational activities of the DRM are built and illustrated using Vitech CORE 9. A functional analysis of the DRM is performed based on the operational activities to identify the key functions and their enhanced functional flow block diagrams (EFFBDs) required to implement the operational activities. These EFFBDs are built and illustrated using Vitech CORE 9.

Chapter 4 describes the design of experiments and the simulation models that are developed to facilitate the analysis of the kill chain of the selected capability. As the kill chain is similar to a process flow, ExtendSim 9.0 is used to build the model. Activity blocks are used to model the processes within the expanded kill chain.

Chapter 5 proposes three possible alternative concept of operations (CONOPS) for the MTX and presents the analysis of these alternatives. Chapter 6 discusses the observations and insights, and provides concluding remarks and details the possible future work.

CHAPTER 2:
Approach and Capability Mapping

This chapter describes the research approach and system engineering tools used for this study. This is followed by a hierarchical decomposition to the second tier reflecting the capability areas in DOD's JCA Framework [23]. This chapter explores the potential capabilities that manned-unmanned teaming can deliver. Specifically, the identified unmanned-unmanned teaming capabilities are mapped to the Tier-1 capabilities of the JCA Framework to ensure that the identified capabilities are relevant to the current capability requirements.

2.1 Approach

Figure 2.1 shows an overview of the system analysis approach used in this study.

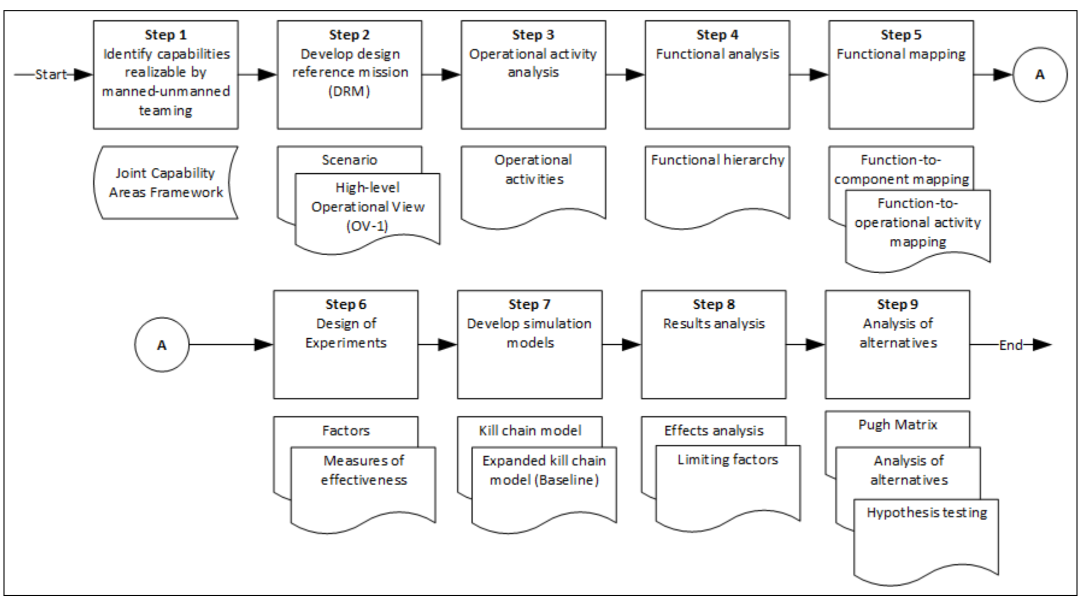
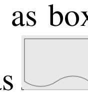


Figure 2.1: A nine-step process is used in this study to investigate the expanded kill chain of manned-unmanned teaming for future strike operations. System engineering tools are used where appropriate to facilitate the analysis.

In the figure, the processes or activities are depicted as boxes , and the documents generated from the process or activities are depicted as . When external data or infor-

mation is used, these are depicted using . The details of each step in the approach is described in the following paragraphs.

Step 1: Capability Identification and Mapping

The first step involves the identification of capabilities that could be realized by manned-unmanned teaming. For this, the JCA Framework is referenced and all capabilities identified are mapped back to the Tier-1 capability areas in the framework. Refer to Section 2.2 for details of the potential manned-unmanned capabilities identified.

Step 2: Develop Design Reference Mission

From the capabilities identified from Step 1, a specific capability is selected for further analysis. To this end, a DRM is developed. The DRM contains a description of the scenario, an assessment of the threats, and a definition of the mission. Refer to Chapter 3, Section 3.2 and 3.4 for details of the scenario and mission definition respectively.

Step 3: Operational Activity Analysis

The high-level operational activities for the DRM are then derived and illustrated using in Vitech CORE. This involves the development of the basic kill chain and the expanded kill chain for the scenario and mission. Each top-level operational activity is further decomposed to the next level. The heuristics in CORE facilitates the subsequent process of functional analysis and mapping. Refer to Chapter 3, Section 3.6 for details on the operational activity analysis.

Step 4: Functional Analysis

Functional analysis is performed in this step. From the operational activities identified, system functions are defined to enable the identification of the key functional requirements of the system or system of systems (SoS). The results of the analysis is a functional hierarchy decomposition of the manned-unmanned teaming capability of interest. Refer to Chapter 3, Section 3.7 for details of the functional analysis.

Step 5: Functional Mapping

To facilitate a better understanding of the relationships between the components of the SoS, a mapping of the functions to the operational activities and the components is performed. For each operational activity, functions necessary for its implementation are

mapped. Each function is then allocated to one component in the function-to-component mapping. Heuristics in CORE ensures that each function is allocated to only one component. Refer to Chapter 3, Section 3.8 and 3.9 for details of the mapping of functions to operational activities and components respectively.

Step 6: Design of Experiments

Design of experiments is performed. To this end, design factors, measures of effectiveness and performance are defined in this step. The design of experiment is accomplished using JMP Pro 10, a statistical analysis program. Chapter 4 describes the details of this step.

Step 7: Develop Simulation Models

The basic kill chain and the expanded kill chain is modeled in ExtendSim. Simulation runs of the model enable the determination of the cycle time for the kill chain and the expanded kill chain. The cycle time of specific processes within the expanded kill chain are also determined through the simulation. Refer to Chapter 4, Section 4.5 and 4.6 for details of the kill chain and expanded kill chain simulation models respectively.

Step 8: Results Analysis

Results from the simulation are analyzed to determine the main effects from the design factors. Effect analysis is accomplished using the statistical analysis program, JMP Pro 10. The identification of factors that has the largest effects enable the development of refinements in tactics, techniques and procedures (TTPs) for the manned-unmanned teaming operation. Limiting factors of the manned-unmanned teaming operation are identified. Refer to Chapter 4, Section 4.7 for details of the analysis.

Step 9: Analysis of Alternatives

Three alternatives are proposed in this step. The proposed alternatives serve to address or mitigate the identified limiting factors of the manned-unmanned teaming operation. Each alternative is analyzed for its effectiveness in addressing or mitigating the identified limiting factors. Modifications are made to the simulation models, where necessary, to enable the study of the effectiveness of the alternatives. Where possible, future concepts of operations are also proposed. Chapter 5 presents details of the analysis of alternatives.

2.2 Joint Capability Areas

Capability needs are articulated as a JCA document and form the JCA Framework [23]. The JCA Framework is a collection of capabilities functionally grouped to support capability analysis, strategy development, investment decision making, capability portfolio management and capabilities-based force development and operational planning [23]. The JCA is divided into nine Tier-1 functional areas. The terminology (shown in *italics*) for the respective capability areas are quoted directly from the JCA Framework to preserve the formal definitions of the capability areas.

2.2.1 Force Support

This area focuses on *the ability to establish, develop, maintain and manage a mission ready Total Force*. This area is decomposed into the sub-areas of Force Management, Force Preparation, Human Capital Management and Health Readiness.

2.2.2 Battlespace Awareness

This area focuses on *the ability to understand dispositions and intentions as well as the characteristics and conditions of the operational environment that bear on national and military decision-making by leveraging all sources of information to include Intelligence, Surveillance, Reconnaissance, Meteorological, and Oceanographic*. This area is decomposed into the sub-areas of Intelligence, Surveillance and Reconnaissance and Environment.

2.2.3 Force Application

This area focuses on *the ability to integrate the use of maneuver and engagement in all environments to create the effects necessary to achieve mission objectives*. This area is further decomposed into the two areas of maneuver and wngagement.

2.2.4 Logistics

This area focuses on *the ability to project and sustain a logistically ready joint force through the deliberate sharing of national and multi-national resources to effectively support operations, extend operational reach and provide the joint force commander the freedom of action necessary to meet mission objectives*. This area is decomposed into sub-areas of

deployment and distribution, supply, maintain, logistics services, operational contract support, engineering and installations support.

2.2.5 Command and Control

This area focuses on *the ability to exercise authority and direction by a properly designated commander or decision maker over assigned and attached forces and resources in the accomplishment of the mission*. It is decomposed into the sub-areas of organization, understanding, planning, deciding, directing and monitoring.

2.2.6 Net-Centric

This area focuses on *the ability to provide a framework for full human and technical connectivity and interoperability that allows all DOD users and mission partners to share the information they need, when they need it, in a form they can understand and act on with confidence, and protects information from those who should not have it*. It is decomposed into the sub-areas of Information transport, enterprise services, net management and information assurance.

2.2.7 Protection

This area focuses on *the ability to prevent/mitigate adverse effects of attacks on personnel (combatant/non-combatant) and physical assets of the United States, allies and friends*. It is decomposed into the sub-areas of prevention, mitigation, and research and development.

2.2.8 Building Partnerships

This area focuses on *the ability to interact with partner, competitor or adversary leaders, security institutions, or relevant populations by developing and presenting information and conducting activities to affect their perceptions, will, behavior, and capabilities in order to build effective, legitimate, interoperable, and self-sustaining strategic partners*. This includes the sub-areas of communication and policy shaping.

2.2.9 Corporate Management and Support

This area focuses on *the ability to provide strategic senior level, enterprise-wide leadership, direction, coordination, and oversight through a chief management officer function*. It

includes the sub-areas of advisory and compliance, strategy and assessment, information management, acquisition, and program, budget and finance.

2.3 Potential Manned-Unmanned Capabilities

The unique system characteristics of an aerial manned-unmanned teaming (MUM-T) present opportunities for the realization of capabilities that have been traditionally undertaken by manned aircraft. Manned aircraft's performance and endurance are limited by the physical traits and capabilities of the operator. Integration of manned platforms with autonomous UAV systems enables the reduction of workload off the operator, thereby enhancing the operator's efficacy during operations.

The potential capabilities from teaming manned platforms with unmanned systems are identified through extrapolation of current technologies in UAV systems, sensor systems and weapon systems. The key advantages of employing UAV systems are in the areas of resource efficacy, autonomy and mitigation of risk to human lives. These potential capabilities that can be performed by manned and unmanned teams are described in the subsequent paragraphs.

2.3.1 Manned-Unmanned Teaming

The teaming of manned and unmanned aircraft could possibly be a disruptive technology in future combat. The MUM-T concept calls for the establishment of a command data link between a manned aircraft and one or more unmanned aircraft, operating as a single unit towards the achievement of a specific mission objective. The concept was employed in the late 1960s when the USAF modified sixteen C-130s (designated DC-130) to deploy AQM-34 Firebee drones. Airborne DC-130s controlled these drones for reconnaissance and electronic warfare operations. Each DC-130s had the ability to deploy and control up to four drones simultaneously [24]. In 2006, Lockheed Martin successfully demonstrated the MUM-T (strike) concept using an AH-64D Longbow Apache helicopter, a UH-60 Black Hawk helicopter and an RQ-5B Hunter UAV [6]. Nonetheless, there have been limited operational applications of MUM-T. Even in such operations where MUM-T was employed, the UAVs primarily performed the ISR role for the purpose of reconnaissance, target location and designation. In 2014, the U.S. Navy pushed the manned and unmanned teaming concept closer to reality when they successfully demonstrated the safe and seam-

less operations of the launch and recovery of manned and unmanned aircraft off an aircraft carrier [25]. In that test, the USN demonstrated the capability to launch of an F/A-18 Super Hornet from catapult 2 followed by a X-47B UCLASS from catapult 1 within a time period of 90 seconds. In the same test, the USN was also able to land the X-47B and the F-18 Hornet within 90 seconds of each other. This demonstration paved the way for future tests of unmanned aircraft from aircraft carrier in an operationally realistic environment. Figure 2.2 shows a screen grab from a U.S. Navy video of the test [26] posted on the U.S. Navy's official YouTube Channel.

Figure 2.2: An F/A-18 Super Hornet and a X-47B UCLASS lines up on the catapults aboard the USS Theodore Roosevelt (CVN 71) just prior to launch. The tests demonstrated the integration of manned and unmanned aircraft onboard an aircraft carrier and the ability for unmanned aircraft to operate safely and seamlessly with manned aircraft. (from [26])

2.3.2 Potential Application of Manned-Unmanned Teaming

The following paragraphs explore the possibilities where the application of manned-unmanned teaming, including unmanned systems with swarming capabilities, provides for enhanced operational efficacy.

Intelligence, Surveillance and Reconnaissance

UAVs have been traditionally employed in the role of intelligence, surveillance and reconnaissance. The military can effectively employ a UAV system with swarming capabilities,

enabling an organic coordinating capability to maximize the ISR coverage while avoiding detection and threats. Teamed with a manned fighter package, the swarm UAV system can perform the role of forward scouts during operations, relaying real-time imagery to enhance the strike package's battle-space situational awareness.

Maritime Surveillance

Similar to ISR, a swarm UAV system teamed with a maritime surveillance aircraft performing the role of an airborne control can effectively provide a maritime surveillance (MS) capability in, for example, counter-piracy and maintenance of open sea lanes of communication over a larger area. A swarm UAV system teamed with a maritime surveillance aircraft will be capable of providing wider coverage and a longer persistence compared to multiple maritime surveillance aircraft, which may be susceptible to crew fatigue and resource limitations.

Search and Rescue

A swarming UAV system can provide a multiplier effect to a search and rescue (SAR) mission through its organic coordinating capability to achieve more efficient search patterns to achieve efficacy in the search and location of casualties. The use of unmanned swarm systems for SAR removes the need for the SAR team to operate in a hostile area unnecessarily. Nonetheless, a manned aircraft will likely still need to be deployed into the hostile area for recovery once the casualty has been located by the swarm system.

Defensive Counter Air and Offensive Counter Air

A system of UAVs teamed with manned aircraft could realize a multiplier effect to both DCA and OCA operations through the saturation of enemy air units, in either a defensive or offensive posture. This could potentially require less resources while providing a more comprehensive coverage. However, a major consideration of such an employment will be in the aspect of weapon release authority, which will still require a man-in-the-loop.

Manned-Unmanned Teaming (Strike)

The teaming of manned and unmanned aircraft in precision strike missions could provide enhancements in range and payload. For example, UAVs can be employed as missile trucks to increase the payload of manned fighters, or as forward ISR aircraft for target location

and designation. The use of UAVs for strike also minimizes the risk of loss of human lives as it removes the pilot from direct line of fire.

Humanitarian Assistance and Disaster Relief

A system of UAVs can be employed in humanitarian assistance and disaster relief (HADR) missions to enhance the supply chain's efficiency. Smaller and cheaper than helicopters, a flight of light to medium-lift unmanned aircraft, teamed with a single airborne control platform, may be able to provide the necessary lifting capacity to disaster areas that are inaccessible by road or conventional transport aircraft.

Rapidly Deployable Network

A swarming UAV system consisting of UAVs with communications relay capabilities can provide an effective communications network in areas with none or degraded communications infrastructure. The swarm UAV system can provide, for example, an aerial cellphone network round-the-clock through synchronized holding maneuvers over the desired area of operations.

Suppression of Enemy Air Defense and Destruction of Enemy Air Defense

Autonomous UAVs can be employed as a forward package to provide suppression of enemy air defense (SEAD) and destruction of enemy air defense (DEAD) capabilities for a following strike package consisting of manned fighters. UAVs can be equipped with a targeting system or configured to carry high-speed anti-radiation missile (HARM) for use against enemy air defense systems. Such a package of UAV system could be employed to destroy enemy air defense radar systems and cause the enemy air defense to "go blind," enabling the safe ingress of the strike package.

Electronic Warfare

UAVs can be employed in selected electronic warfare (EW) missions to provide electronic attack (EA), ELINT and radar warning receiver (RWR) capabilities. An swarming UAV system can provide a more effective and coordinated EW capability at lower risk. When teamed with manned aircraft, such UAV systems can provide coordinated off-axis EW capabilities.

Stand-Off Jammer and Support Jammer

When teamed with manned aircraft, a UAV system could provide a highly effective stand-off jammer (SOJ) or support jammer (SPJ) capability to a strike package, either through forward deployment or off-axis jamming.

2.4 Mapping to Joint Capability Areas Framework

Figure 2.4 shows the mapping of potential swarm capabilities to the JCA Framework. The potential manned-unmanned teaming capabilities (shaded in grey diagonal lines) described above are mapped to five of the nine Tier-1 capabilities in the JCA Framework. Tier-1 capabilities that are not mapped to potential manned-unmanned teaming capabilities are omitted for brevity.

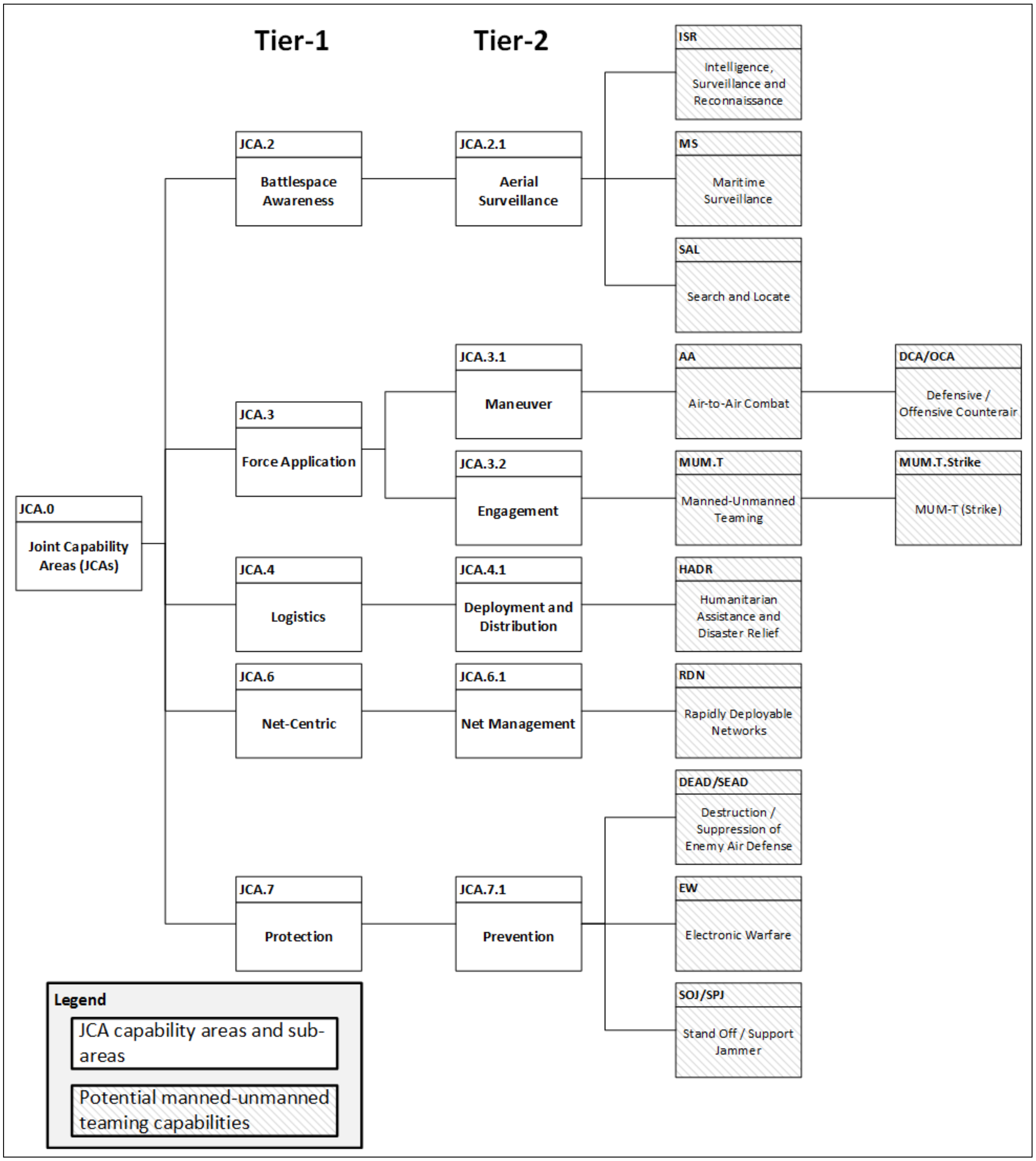


Figure 2.3: Mapping of potential manned-unmanned teaming capabilities to the JCA framework.

This study will focus on the capability area of "force application." Specifically, the study looks into the sub-area of "engagement" as realized by manned-unmanned teaming towards the accomplishment of a MUM-T (strike) operation.

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CHAPTER 3:
Design Reference Mission

Among the potential capabilities identified for manned-unmanned teaming in the preceding chapter, the manned-unmanned teaming (MUM-T) (strike) capability is perhaps the most complex, requiring close coordination and positive control of the unmanned aircraft [6]. The use of manned and unmanned teaming for strike has also never been performed. Therefore, this research used the MUM-T (strike) capability for this study. As part of the study, a DRM is developed for this capability. The DRM describes the projected operational environment of the mission, the mission success requirements, a definition of the mission capabilities and operational activities, and a description of the mission execution [27]. The projected operational environment includes both typical operational and environmental conditions, and also includes a brief threat assessment specific to the mission. The mission execution description elaborates on the expanded kill chain for the mission and highlights selected operational situations.

3.1 Actors

For the purpose of DRM development, the following fictitious actors, BLUELAND and REDLAND, are assumed. In addition, DOD's definition of a manned-unmanned teaming is adopted. It states that manned-unmanned teaming (MUM-T) refers to the relationships established between manned and unmanned systems personnel prosecuting a common mission as an integrated team. More specifically, manned-unmanned teaming (MUM-T) is the overarching term used to describe platform interoperability and shared asset control to achieve a common operational mission objective [6].

3.1.1 BLUELAND

The BLUELAND has a fleet of advanced UAVs that has been used to conduct strikes against transnational terrorist threat (T3) targets. BLUELAND has, in recent years, invested heavily in the research and development of swarm technology for the UAVs. These investments have paid off, delivering BLUELAND with the capability to conduct selected combat missions employing swarm tactics. Under BLUELAND's distributed air wing con-

cept [16], BLUELAND fighters and UCAVs are embarked on their respective naval surface vessels. The UCAVs are operated from a larger version of the next-generation escort carrier (CVEX) [28], the evolution of next-generation escort carrier (CVEX 2), that is capable of launching and recovering large UCAVs while the fighters operate from aircraft carriers.

BLUELAND Manned Fighters

The BLUELAND manned fighters in the 202X time frame are fifth-generation fighters, with a combat effectiveness on parity with the F-35C Lightning II. The fighters are advanced multi-role all weather, day and night, very low observable (VLO) fighters. The weapons are carried in internal weapons bay and the air-to-ground (AG) weapons load out consists of two joint direct attack munitions (JDAMs) or eight small diameter bombs (SDBs). In addition to the Link16 data link, the BLUELAND fighter is equipped with a low probability of intercept (LPI) data link that provides intra-ship (fighter-to-fighter) communications and UCAV command link capability. The BLUELAND fighter has a combat range of up to 700 nautical miles (nm). The BLUELAND manned fighters can be launched from aircraft carriers and land bases.

BLUELAND Unmanned Combat Aerial Vehicles

The BLUELAND UCAVs in the 202X time frame is a supersonic VLO aircraft with LPI data links and an internal weapons carriage bay. Similar to the BLUELAND fighters, the AG weapons load out of the UCAV is two JDAMs or eight SDBs. The UCAV has a combat range of 2000nm. This enables it to execute strategic strikes deep into A2AD environments or highly contested airspace. The BLUELAND UCAV can be launched from CVEX 2 and land bases.

3.1.2 REDLAND

The REDLAND is a rogue nation that has consistently adopted an aggressive approach to intrusions into its territorial waters. REDLAND has an air force that is a near-peer to BLUELAND's Air Force and has also recently operationalized an aircraft carrier. REDLAND is involved in a sovereignty dispute with several neighboring nations over a group of isles in an area of international waters outside of REDLAND's exclusive economic zone (EEZ). Several skirmishes have already occurred between REDLAND's Air Force and the Air Forces of the neighboring nations.

3.2 Scenario

The scenario is set in the year 202X. REDLAND has been exhibiting increasing aggressive A2AD actions in the littoral waters and waters surrounding a group of disputed islands in international waters. Recently, REDLAND had unilaterally declared an air defense identification zone (ADIZ) over a portion of the international waters that includes the disputed isles. BLUELAND has declared openly that it does not recognize REDLAND's ADIZ and has executed several flight operations in the area to challenge the legitimacy of the ADIZ. BLUELAND intends to heighten its military presence in the area to maintain continued open sea lines of communications (SLOC). BLUELAND operates a number of air bases in the surrounding nations and plans to use these bases as staging bases for its naval air assets. At present, the BLUELAND has deployed an aircraft carrier and a CVEX 2 into the area and there are plans to deploy another aircraft carrier and two more CVEX 2s into the area.

A recent skirmish between REDLAND and BLUELAND units in the waters off the disputed isles resulted in the sinking of a BLUELAND surface vessel. The news of the sinking is widely reported in global media. This results in an increasing anxiety amongst the surrounding nations to a potential escalation of military conflict in the region. Although the sinking did not result in a loss of life for the BLUE LAND Navy, there is an urgent need for BLUELAND to demonstrate its military might in order to deter further aggressions and restore stability to the region. However, BLUELAND is cautious that any military action must be de-escalatory in nature, and an open strike on REDLAND is not tenable. To this end, a covert strategic strike on REDLAND airbases to effectively disable or degrade REDLAND's DCA and OCA capabilities is planned. The strike is to be performed by a team of manned and unmanned aircraft operating as a integrated strike package and will deliver weapons onto REDLAND's airbases.

3.3 Threat Assessment

Threats are categorized as kinetic, cyber and natural. Kinetic threats consist of mainly projectile and ammunition fired from hand-held or ground-based air defense systems. Electronic threats consist of systems utilizing electromagnetic means to degrade and interfere with the operations of the radar system, or achieve deception. This is achieved through the use of either noise for degradation and interference, or false information for deception.

Cyber threats consist of the enemy gaining access to any secured communications or data links. Natural threats consist of weather and terrain. The threats to a manned-unmanned strike operation are described in the following paragraphs.

3.3.1 Kinetic Threats

The MUM-T (strike) package operates at a high altitude, out of range of most small-arms fire and anti-aircraft fire. These systems are unable to effectively engage aircraft flying at altitudes above 30,000 feet. However, threats from advance surface-to-air missiles exist. REDLAND airbases are protected by S-400 class air defense systems. The S-400 class air defense systems has an effective range of between 120km (60nm) to 400km (222nm) up to altitudes of up to 100,000 feet and is integrated with a radar capable of detecting low-signature targets [29].The ability to penetrate deep into the ADIZ is critical to the successful delivery of weapons against the ground targets. Thus, the ability to avoid detection through the employment of VLO aircraft is critical to mission success.

3.3.2 Cyber Threats

Any MUM-T mission requires close coordination and control, so there is a heavy reliance on data link integrity and availability. The data link is critical for mission success. A loss of data link results in a total loss of communications and consequently loss of control over the unmanned aircraft. The employment of LPI data and communications links reduces the risks of compromise of the data and communications links.

3.3.3 Natural Threats

Adverse weather conditions over the targets could mean that a positive location and identification of targets is not possible. As such, it is important that accurate and timely information about the weather over the target area be available to mission planners and the combat commanders. In addition to weather, ground clutter due to terrain or environmental features can also result in the system's inability to accurately resolve a target solution for engagement.

3.4 Mission Definition

Based on intelligence update and analysis, a strategic strike on REDLAND's airbases to inflict sufficient damage to degrade or disable the REDLAND's DCA and OCA capabilities

would provide a sufficiently strong deterrent signal and compel REDLAND to tone down their aggressive posture. As the REDLAND airbases are located deep within the REDLAND ADIZ and defended by heavy air defense, BLUELAND headquarters (HQ) orders a MUM-T (strike) mission. The mission objective is to execute a pre-emptive strategic strike against REDLAND's aircraft and airbase infrastructure. The objective of the strike is to inflict sufficient destruction to the airbase infrastructure and aircraft on ground to cripple REDLAND's air force in the near-term.

The mission order is disseminated to the CVEX 2 and the carrier strike group (CSG). Upon receipt of the mission orders, both CVEX 2 and the CSG commence joint mission planning and prepare the UAVs and aircraft for launch. All UAVs allocated for the mission are equipped with an integrated targeting suite. A total of four manned fighters and eight UCAVs are allocated for this mission. Table 3.1 shows the force structure for the order of battle for the BLUELAND MUM-T (strike) package.

Table 3.1: BLUEFORCE order of battle for MUM-T (strike) package

Asset	**Strength**
Manned fighter	4
Unmanned Combat Aerial Vehicle	8
Aircraft Carrier	1
CVEX 2	1

3.5 Operational Architecture

Figure 3.1 shows the high-level operational view for the MUM-T (strike) DRM.

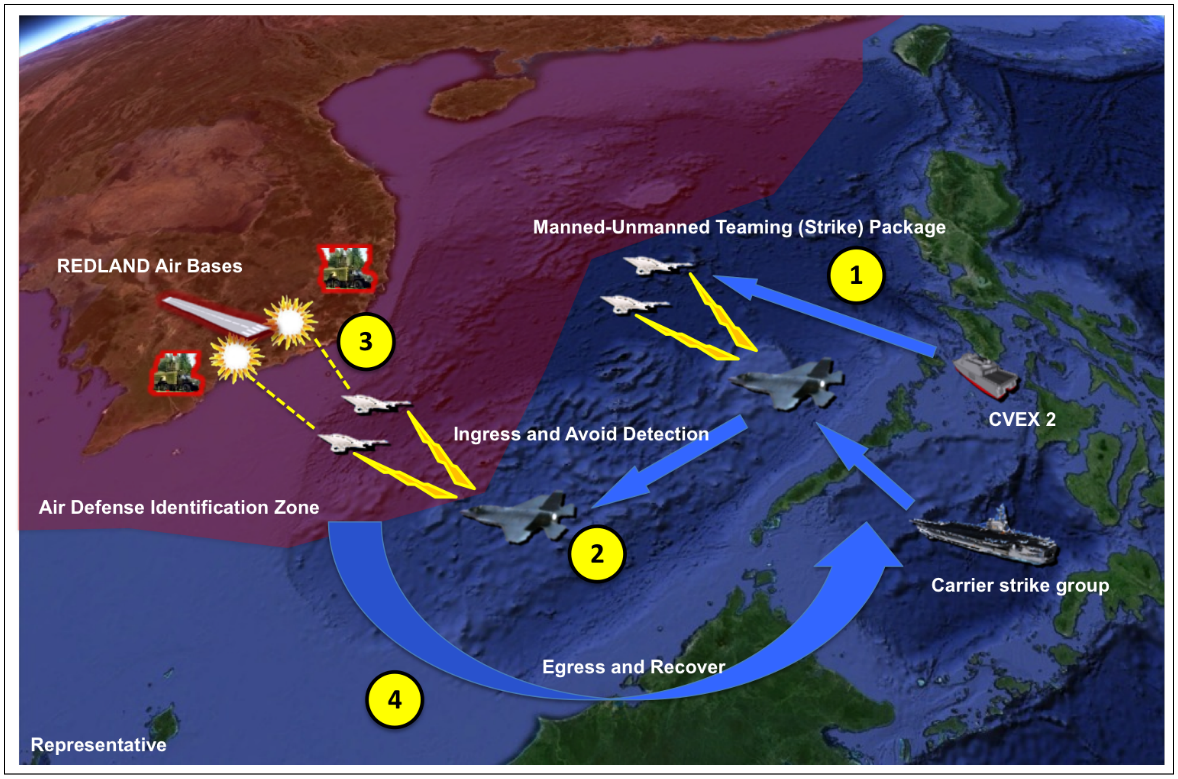

Figure 3.1: MUM-T (strike) DRM high-level operational view, OV-1. The major phases of the operations are "Launch and formation of MUM-T (strike) package," "Ingress towards target," "Target engagement" and "Egress and recovery."

The activities depicted in the operational view is described in the following paragraphs with phases indicated by numerals in the yellow circles.

1. **Phase 1 – Launch and formation of MUM-T (strike) package**: After launch, the manned fighters and the UCAVs transit to a per-determined rendezvous point. The rendezvous point is located outside the REDLAND ADIZ. At the rendezvous point, an airborne link-up between the manned fighters and the UCAVs is accomplished and control of the UCAVs is handed over from the ground control station onboard the CVEX 2 to the manned fighters.
2. **Phase 2 – Ingress towards target**: After the successful airborne link-up of all four manned fighters with the eight UCAVs, the MUM-T (strike) package commences

the covert ingress towards the target. The UAVs are vectored by the manned fighters towards the target deep within the ADIZ. During ingress, the UAVs autonomously locate and identify the targets, and generate the target solution. This is accomplished through information sharing and collaborative sense-making between the UCAVs. The UCAVs also perform autonomous threat avoidance using their onboard sensors. Video feed is piped back to the manned fighters throughout the ingress targeting phase.

3. **Phase 3 – Target engagement**: The UCAVs, being able to penetrate deeper into the ADIZ, are used for target location, identification and designation. Target identification and confirmation is performed by the manned fighter via real-time video feed from the UCAVs. When the UCAVs are within range of the target, and targets having been positively identified, weapon release commands are given by the manned fighters. The ISR UAVs will provide video feed for the manned fighter to perform battle assessment and confirm the destruction of the targets.
4. **Phase 4 – Egress and recovery**: The entire MUM-T package then egresses and returns to their respective bases. Control of the UAVs is handed over to the UAV ground control on the CVEX 2 for UAV recovery. Intelligence debrief is conducted as part of mission debrief.

3.6 Operational Activities Analysis

The MUM-T (strike) mission as defined in Section 3.2 is used to develop the operational activities necessary for the basis of the capability. The operational activities schematics (Operational View - 5b) are built and illustrated using Vitech CORE 9 [30]. Figure 3.2 shows the operational activities of the MUM-T (strike) mission. The "USMC.KC" block represents the USMC kill chain while the preceding and following blocks represent the expanded kill chain.

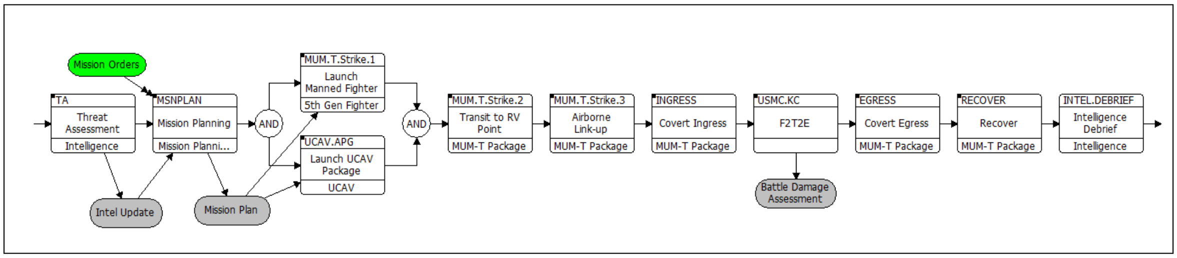

Figure 3.2: MUM-T (strike) operational activities (OV-5b) showing the expanded kill chain to include the pre-requisite operational activities leading up to the traditional kill chain activity of "F2T2E" and the activities after the completion of the traditional kill chain. The traditional kill chain is depicted as a single activity block named "F2T2E."

Each block in the operational activity flow is described in the following paragraphs starting from the left and proceeding to the right. The green box represents the trigger for the start of the specific operational activity that the arrow points to. Grey boxes represents the output and input to the respective operational activities, with arrow point out of the operational activity indicating "output" and arrow pointing into the operational activity indicating "input."

1. **Threat Assessment (TA) –** Upon receipt of the mission orders, a threat assessment is performed for the area of operations. Threat intelligence may come from diverse sources. These sources may include open source intelligence (OSINT), human intelligence (HUMINT), geospatial intelligence (GEOINT), measurement and signature intelligence (MASINT), signal intelligence (SIGINT), cyber and digital network intelligence (CYBINT/DNINT). Threat assessment will also include inputs for DEFCON and THREATCON statuses. The output from the threat assessment is the intelligence update. Figure 3.3 shows the decomposition of the operational activities for threat assessment.

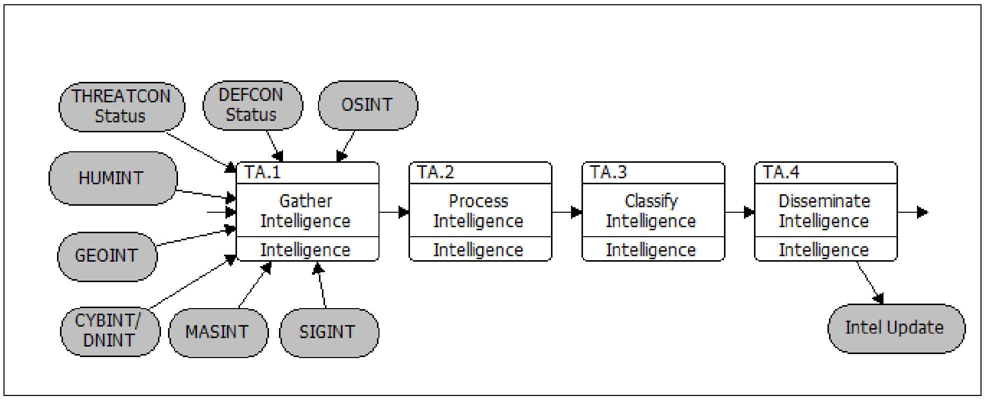

Figure 3.3: Decomposition of threat assessment (TA) operational activity. The decomposition identifies the various intelligence sources, alert postures and threat conditions as inputs and the intelligence update as the output of the operational activity. Four second-level operational activities are identified.

2. **Mission Planning (MSNPLAN)** – This block represents the activities of mission planning. Mission planning is conducted jointly between the mission-planning teams onboard the aircraft carrier and CVEX 2. The output of this function is the Mission Plan. Figure 3.4 shows the decomposition of the operational activities for mission planning.

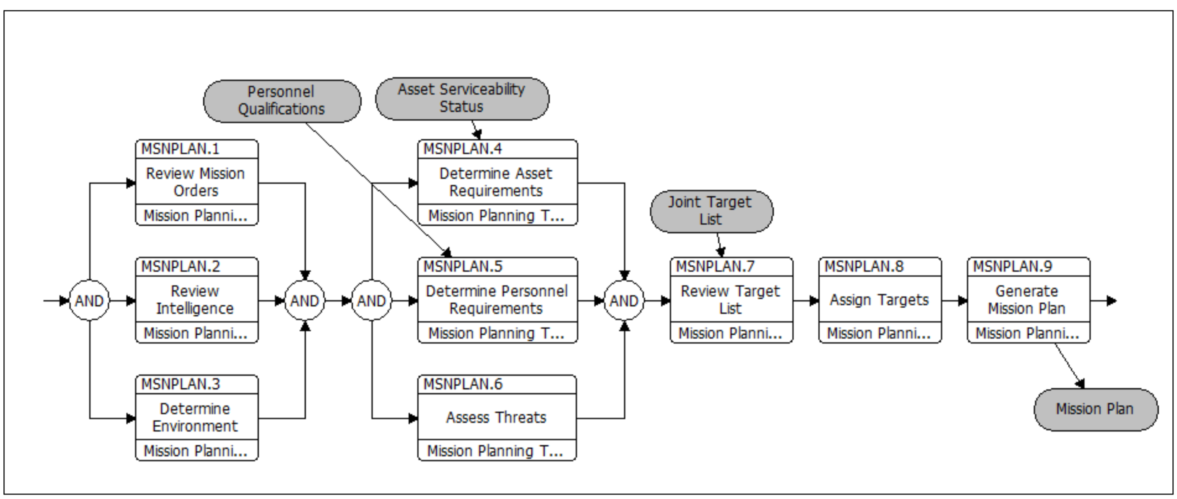

Figure 3.4: Decomposition of mission planning (MSNPLAN) operational activity. The decomposition identifies the necessary second-level activities that must run in parallel, the inputs required and the mission plan as the output from this operational activity. Nine second-level operational activities are identified.

3. **Launch Manned Fighter (MUM.T.STRIKE.1)** – This block represents the launch-

ing of the manned fighters for the mission. This involves the preparation (pre-flight, weapons loading and end-of-runway (EOR) checks) of the fighters for flight and combat.

4. **Transit to RV Point (MUM.T.STRIKE.2)** – This block represents the transition of all air assets after their launch to the designated RV Point. The time taken is dependent on the aircraft's speed, the distance from the launch site to the RV Point and the weather conditions.
5. **Airborne Link-up (MUM.T.STRIKE.3)** – This block represents the handing over of control of the UCAVs to the manned fighters. Once the manned fighters have authenticated and established a secured command data link with the UCAVs, the ground control stations will hand over controls of the UCAVs to the manned fighters. Each manned fighter will assume control over two UCAVs and this force structure forms one MUM-T (strike) unit. Figure 3.5 shows the decomposition of operational activities for airborne link-up.

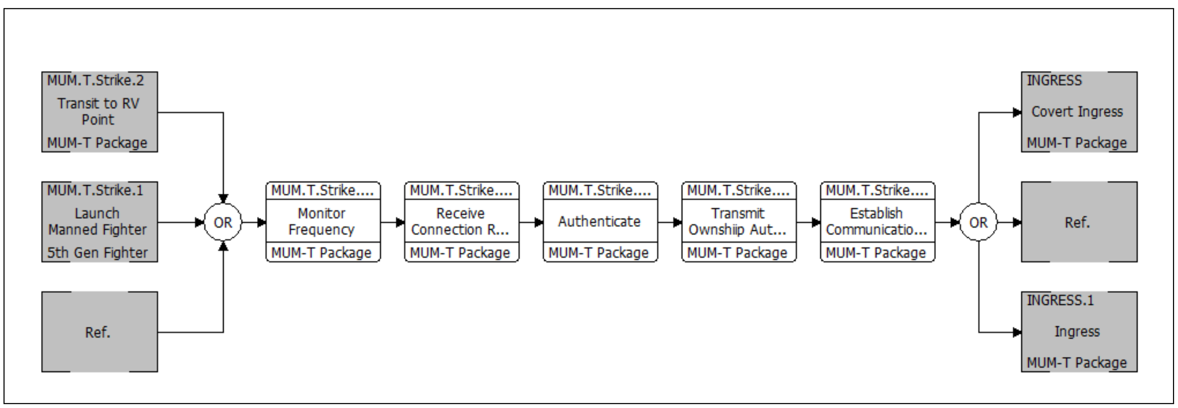

Figure 3.5: Decomposition of airborne link-up (MUM.T.STRIKE.3) operational activity. The decomposition identifies five second-level activities in order for the manned fighter and to establish communications with and obtain positive control of the UCAV

6. **Launch UCAV Package (UCAV.APG)** – This block represents the launching of the UCAV for the mission. This involves preparing (pre-flight, weapons loading and EOR checks) the UCAV and the initializing of the ground control stations for the launch. It is assumed that the UCAVs are equipped with auto take-off and landing (ATOL) capabilities, thus no external pilots are required for the actual take-off control after the EOR checks.
7. **Covert Ingress (INGRESS)** – Once the MUM-T (strike) package is formed, the

package proceeds to ingress towards the area of operations. The package does so covertly, avoiding detection as far as possible.

8. **Find, Fix, Track, Target, Engage (USMC.KC)** – This block represents the traditional USMC kill chain. A detailed decomposition of this block is shown in Figure 3.6. The decomposition identifies target location (Find), designation (Fix), tracking (Track), targeting (Target) and engagement (Engage) as the second-level operational activities in the kill chain. The "WEAPONS" block identifies the quantity of weapons as a resource limitation and limits the number of targets that can be engaged.

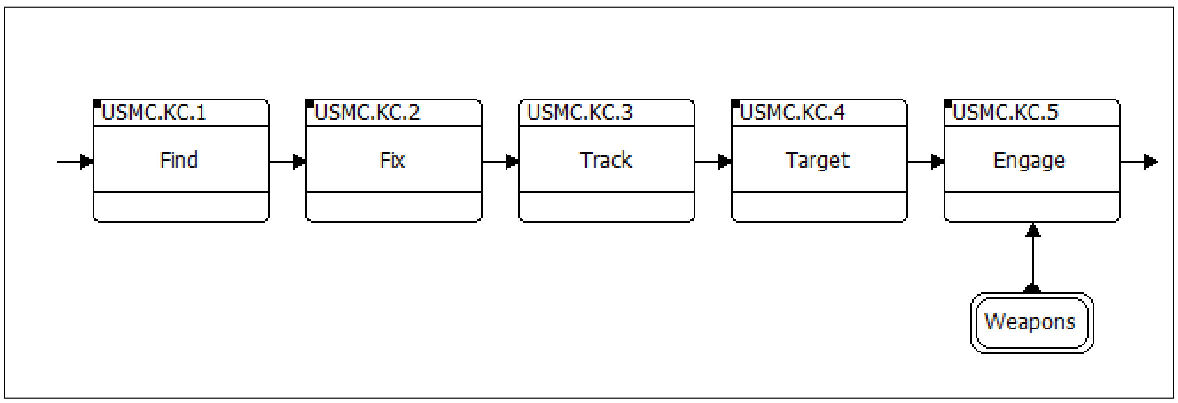

Figure 3.6: USMC kill chain operational activities. The decomposition identifies target location (Find), designation (Fix), tracking (Track), targeting (Target) and engagement (Engage) as the second-level operational activities in the kill chain.

9. **Covert Egress (EGRESS)** – Upon completion of the mission, the MUM-T (strike) package covertly egresses the area of operations.
10. **Return to Base (RECOVER)** – Upon reaching the designated rendezvous point, control of the UCAVs is relinquished by the manned fighters and handed back to the ground control stations. Both manned and unmanned aircraft return to their respective bases, with the UCAVs performing automatic landing.
11. **Intelligence Debrief (INTEL.DEBRIEF)** – Upon return, an intelligence debrief is conducted with the pilots of the mission while video footage from the UCAVs is analyzed by the intelligence community.

3.7 Functional Analysis

The next step of the process is to perform functional analysis for the system described in the DRM. For this study, the system is defined as a MUM-T (strike) unit consisting of one manned aircraft and two unmanned aircraft that are under the control of the manned aircraft. The MUM-T (strike) package (a system of systems) refers to the integrated system of four MUM-T (strike) units, consisting of four manned aircraft and the eight UCAVs under the control of the manned aircraft. Functional analysis begins with the identification of the Level-1 system functions. Seven Level-1 system functions are identified. All EFFBDs are developed and illustrated using Vitech Core 9.

Figure 3.7 shows the decomposition of the seven system functions into their respective sub-functions. These functions are decomposed into their respective Level-2 sub-functions. These functions and sub-functions are described in the following subsections and paragraphs.

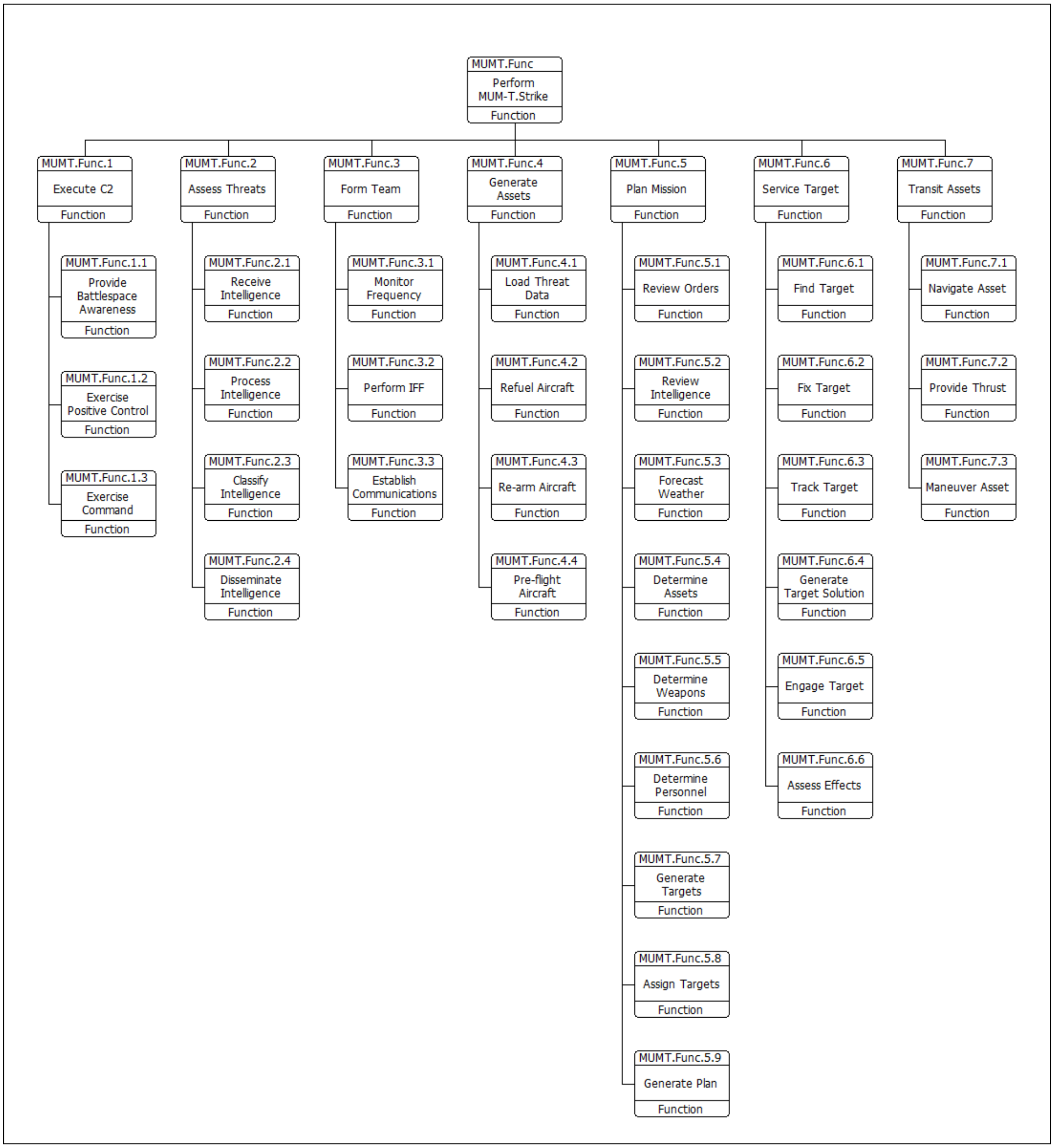

Figure 3.7: Functional hierarchy of MUM-T (strike) system. A total of seven Level-1 functions are identified. Their respective sub-functions are detailed in this figure.

3.7.1 Execute Command and Control

Figure 3.8 shows the functional decomposition for the "Execute command and control (C2)" function. This function is prevalent in all other functions. This function provides the

manned aircraft with the capability to exercise positive control over the two UCAVs during the operation. This function also provides the UCAVs with the necessary autonomous capability when operating as a swarm with the other UCAV in the package. The sub-functions of “Execute C2” are described in the following paragraphs.

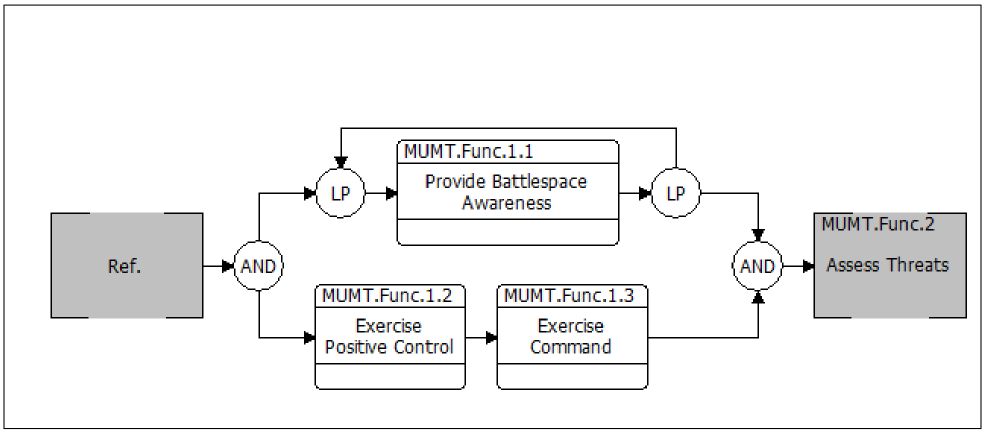

Figure 3.8: Execute command and control (C2) EFFBD. This function is prevalent during all phases of the operation.

Provide Battlespace Awareness – This function provides the manned fighter with the battlespace situation awareness necessary for decision making. This may be accomplished through the provision of a real-time recognized air situation picture built from onboard or off-board sensors, including target tracks, video imagery and threat information generated by the UCAVs.

Exercise Positive Control – This function provides the manned fighter with the capability to have positive control over the UCAVs. Positive controls will include commands to maneuver, to execute targeting actions and to release weapons. On the UCAVs, this function provides the UCAV with limited capability to exhibit autonomous behaviors such as obstacle avoidance, active threat avoidance and targeting functions of location and designation.

Exercise Command – This function enables the manned fighter to perform the role of Mission Commander and the ability to make executive decisions pertaining to the conduct of the mission.

3.7.2 Assess Threats

Figure 3.9 shows the functional decomposition for the "Assess Threats" function. This function provides the joint mission-planning team with the capability to perform threat assessment during the joint mission-planning phase. This is accomplished through the provision of threat database and intelligence support. The sub-functions of"Assess Threat" are described in the following paragraphs.

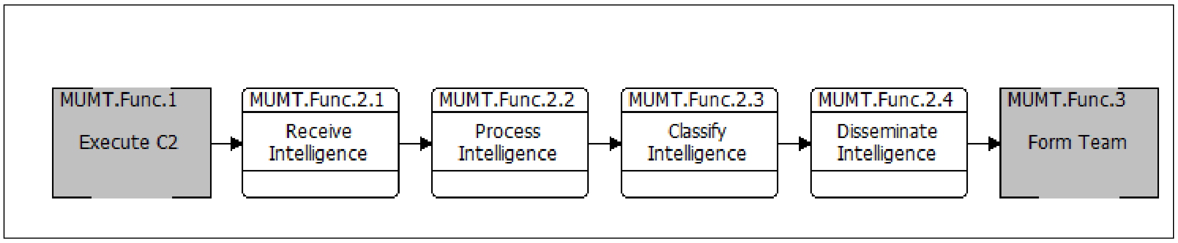

Figure 3.9: Assess threats EFFBD.

Receive Intelligence – This function provides the joint mission-planning team with the capability to receive intelligence reports and updates from the various intelligence generating nodes.

Process Intelligence – This function provides the joint mission-planning team with the capability to process the received intelligence for use towards threat assessment for the mission. The capability also enables the joint mission-planning team to generate the necessary threat databases formatted for uploading onto the manned fighters and UCAVs.

Classify Intelligence – This function provides the joint mission-planning team with the ability to classify processed intelligence according to its relevance to the mission.

Disseminate Intelligence – This function enables the processed and classified intelligence to be packaged into a format suitable for the expeditious dissemination to all elements within the strike package.

3.7.3 Form Team

Figure 3.10 shows the functional decomposition of the "Form Team" function. This function provides the capability for the establishment data links between the elements of the strike package. This includes intra-manned aircraft and intra-UCAV data links as well as

data links between the manned aircraft and the UCAVs. The sub-functions of"Form Tea" are described in the following paragraphs.

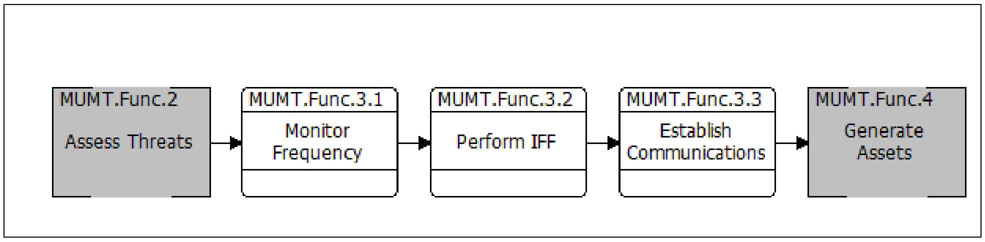

Figure 3.10: Form team EFFBD.

Monitor Frequency – This function provides the elements within the strike package with the capability to monitor a wide spectrum of radio transmission frequency for the purpose of communications with allied units and within the strike package. This includes the simultaneous monitoring of both civilian and military frequency of 121.5 MHz (International Air Distress) and 243.0 MHz (Military Air Distress), respectively.

Perform Identification Friend or Foe (IFF) – This function provides the capability for the elements within the strike package to interrogate, authenticate and identify external systems as either a friendly or unidentified system.

Establish Communications – This function enables the elements within the strike package to establish secured and LPI communications within the package. The elements are equipped with the necessary emissions control (EMCON) protocols and cryptography.

3.7.4 Generate Assets

Figure 3.11 shows the functional decomposition of the "Generate Assets" function. This function defines the ability to perform aircraft generation. The capability includes all logistics and administrative support necessary for the expeditious generation of both manned and unmanned air assets. The following paragraphs describe the sub-functions of "Generate Asset."

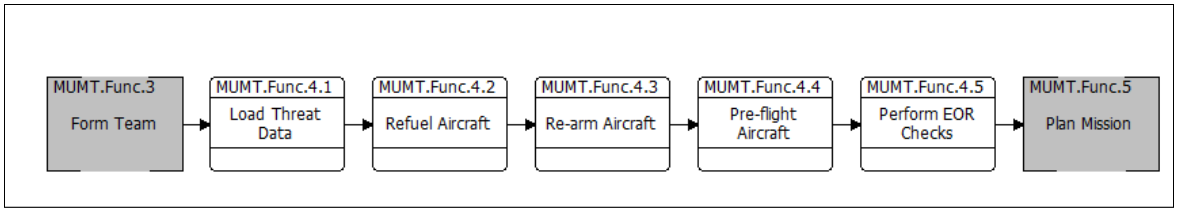

Figure 3.11: Generate assets EFFBD.

Load Threat Data – This function enables the loading of the threat library in the appropriate format onto the air asset, regardless of the medium. The threat data provides the air asset with an onboard autonomous threat avoidance capability based on the threat detected.

Refuel Aircraft – This function enables the expeditious refuel of the air asset in preparation for the mission.

Re-arm Aircraft – This function provides the capability to expeditious load the necessary weapons and munitions onto the aircraft in preparation for the mission. The munitions may include all applicable air-to-surface, air-to-ground and air-to-air weapons and munitions.

Pre-flight Aircraft – This function provides the logistics support capability to perform the necessary operational and maintenance inspections and tests to ascertain that the aircraft is airworthy and mission capable.

Perform End-of-Runway Checks – This function provides the capability for the aircraft to be given a final check by the crew chief prior to the aircraft taking off.

3.7.5 Plan Mission

Figure 3.12 shows the functional decomposition of the “Plan Mission” function. This function provides the capability to perform and coordinate joint mission-planning between two or more mission planning facilities. This provides the capability to communicate through verbal, imagery and video, the information necessary for joint mission-planning with an off-site mission planning facility. The following paragraphs decribe the sub-functions for“Plan Mission.”

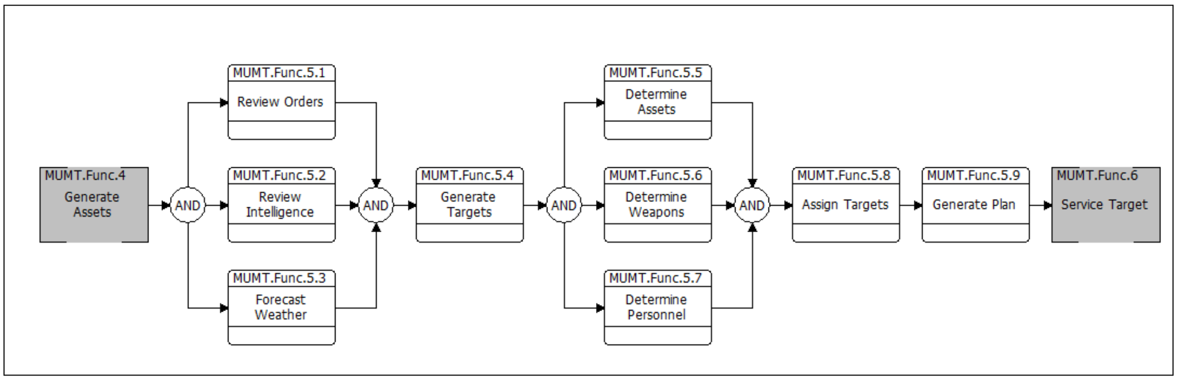

Figure 3.12: Plan mission EFFBD.

Review Orders – This function provides the capability to review the mission tasking order received.

Review Intelligence – This function provides the capability to review and analyze the intelligence provided for the purpose of developing the threat data for the mission.

Forecast Weather – This function provides the capability to obtain or receive weather forecast over the area of operations for the purpose of mission planning.

Generate Targets – This function provides the capability for the joint mission-planning team comprising of the mission planners onboard the aircraft carrier and the CVEX 2 to generate a target list for the mission.

Determine Assets – This function provides the capability for the joint mission-planning team to determine and allocate the assets for the mission. This includes the holistic visibility of the availability of assets embarked on all launch platform tasked by the mission order.

Determine Weapons – This function provides the capability for determination of the appropriate weapons to be employed against the assigned targets.

Assign Targets – This function provides the capability to assign targets to the selected assets. Depending on the target characteristics, specific targets may be assigned to a specific assets employing a specific weapon.

Generate Plan – This function provides the capability to generate the final mission plan for both manned and unmanned assets. The plan contains all the required information for the conduct of the mission.

3.7.6 Service Target

The decomposition for this function was shown previously in Figure 3.6. This function delivers the capability to locate, identify, and engage the target. This function and its subfunctions are traditionally known as the kill chain. Recall that for this study, the USMC kill chain is used.

Find Target – This function provides the capability to detect targets through the utilization of various means. Such means may include imagery, video, and electronic means.

Fix Target – This function provides the capability to determine the location of a target, in particular, its location relative to the system as well as its geo-location.

Track Target – The tracking function provides the capability to continuously geo-locate the target relative to the system.

Generate Target Solution – This function provides the system with the capability to generate the necessary information, such as weapons release point, for a particular target based on ownship pose and the existing environmental and atmospheric conditions to achieve the highest probability of hit by the weapon.

Engage Target – This function provides the capability to release or employ the weapon against the target.

3.7.7 Transit System

Figure 3.13 shows the functional decomposition of the "Transit System" function. This function delivers the capability for the system to transit from one point to another.

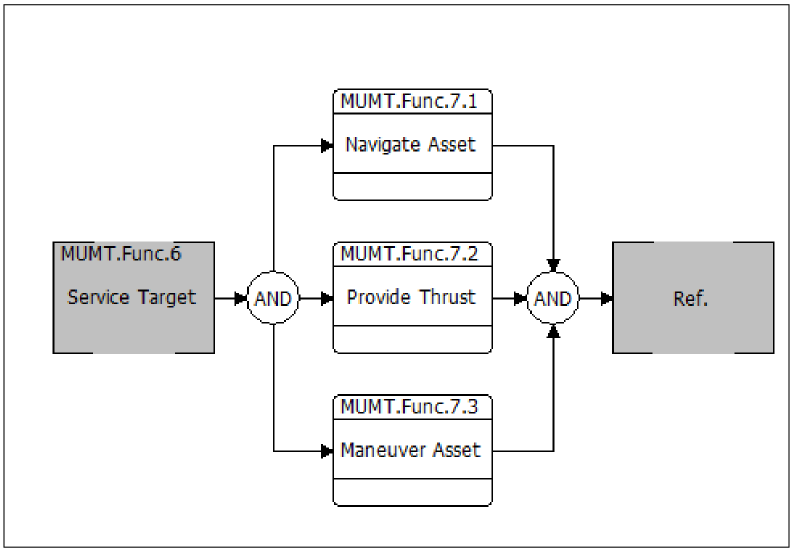

Figure 3.13: Transit system EFFBD.

Navigate Asset – This function provides the system with the capability to perform navigation to a desired location based on inputs from both Earth-based, onboard and off-board navigation systems and beacons.

Provide Thrust – The function provides an organic system capability to provide a motive force to achieve translation.

Maneuver Asset – This function provides the system with the ability to change its pose, speed, heading or location in space.

3.8 Function to Operational Activity Mapping

With the identification and definition of the functions for a MUM-T (strike) operation, the functions are then mapped to the operational activities. The operational activities for a MUM-T (strike) operation shown previously in Figure 3.2. Table 3.2 shows the mapping of functions that are identified to implement the specific operational activities.

Table 3.2: Function-to-operational activity mapping.

Operational Activity	**Description**	**Implemented by**
TA	Threat assessment	MUMT.Func.2 Assess threats MUM.T.Func.2.1 Receive intelligence MUM.T.Func 2.2 Process intelligence MUM.T.Func.2.3 Classify intelligence MUM.T.Func.2.4 Disseminate intelligence
MSNPLAN	Mission planning	MUMT.Func.5 Plan mission MUMT.Func.5.1 Review orders MUMT.Func.5.2 Review intelligence MUMT.Func.5.3 Forecaset weather MUMT.Func.5.4 Generate targets MUMT.Func.5.5 Determine assets MUMT.Func.5.6 Determine weapons MUMT.Func.5.7 Determine personnel MUMT.Func.5.8 Assign targets MUMT.Func.5.9 Generate plan
MUM.T.Strike.1	Launch manned fighter	MUMT.Func.4 Generate assets MUMT.Func.4.1 Load threat data MUMT.Func.4.2 Refuel aircraft MUMT.Func.4.3 Re-arm aircraft MUMT.Func.4.4 Pre-flight aircraft

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Table 3.2 – *Continued from previous page*

Operational Activity	**Description**	**Implemented by**
UCAV.APG	Launch UCAV	MUMT.Func.4 Generate assets MUMT.Func.4.1 Load threat data MUMT.Func.4.2 Refuel aircraft MUMT.Func.4.3 Re-arm aircraft MUMT.Func.4.4 Pre-flight aircraft
MUM.T.Strike.2	Transit to RV point package	MUMT.Func.1 Execute C2 MUMT.Func.7 Transit assets MUMT.Func.7.1 Navigate asset MUMT.Func.7.2 Provide thrust MUMT.Func.7.3 Maneuver assets
MUM.T.Strike.3	Airborne link-up	MUMT.Func.1 Execute C2 MUMT.Func.1.2 Exercise positive control MUMT.Func.1.3 Exercise command MUMT.Func.3 Form team MUMT.Func.3.1 Monitor frequency MUMT.Func.3.2 Perform IFF MUMT.Func.3.3 Establish communications
INGRESS	Covert ingress	MUMT.Func.1 Execute C2 MUMT.Func.1.1 Provide battlespace awareness MUMT.Func.1.2 Exercise positive control MUMT.Func.1.3 Exercise command MUMT.Func.2 Assess threats MUMT.Func.7 Transit assets MUMT.Func.7.1 Navigate asset

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Table 3.2 – *Continued from previous page*

Operational Activity	**Description**	**Implemented by**
		MUMT.Func.7.2 Provide thrust MUMT.Func.7.3 Maneuver assets
USMC.KC	Find, Fix, Track Target, Engage	MUMT.Func.6 Servie target MUMT.Func.6.1 Find target MUMT.Func.6.2 Fix target MUMT.Func.6.3 Track target MUMT.Func.6.4 Generate target solution MUMT.Func.6.5 Engage target MUMT.Func.6.6 Assess effects
EGRESS	Covert egress	MUMT.Func.1 Execute C2 MUMT.Func.1.1 Provide battlespace awareness MUMT.Func.1.2 Exercise positive control MUMT.Func.1.3 Exercise command MUMT.Func.2 Assess threats MUMT.Func.7 Transit assets MUMT.Func.7.1 Navigate asset MUMT.Func.7.2 Provide thrust MUMT.Func.7.3 Maneuver assets
INTEL.DEBRIEF	Intelligence debrief	MUMT.Func.2 Assess threats MUMT.Func.2.1 Receive intelligence MUMT.Func.2.2 Process intelligence MUMT.Func.2.3 Classify intelligence MUMT.Func.2.4 Disseminate intelligence

3.9 Function to Component Mapping

Next, the functions are mapped to the components of the SoS. The components of the SoS are shown in Table 3.3.

Table 3.3: Components of the MUM-T (strike) system of systems.

Component	Description
Manned fighter	A manned carrier-based fighter aircraft with stealth capabilities.
Unmanned aircraft	An unmanned carrier-based unmanned stealth aircraft capable of weapons employment.
Intelligence team	Responsible for the threat assessment and the generation of intelligence and threat data. Conducts post-mission intelligence debrief.
Joint mission-planning team	Responsible for the joint planning of the MUM-T (strike) mission.
Launch platform (aircraft carrier)	Responsible for the generation of mission-capable fighter aircraft, and the launch and recovery of the fighter aircraft.
Launch platform (CVEX 2)	Responsible for the generation of mission-capable UCAV, and the launch and recovery of the UCAVs.

Table 3.4 shows the mapping of functions to components. This mapping is accomplished using Vitech CORE 9. The heuristics algorithm within Vitech CORE ensures that each function is only allocated to (performed by) one component. However, a component may be allocated to (perform) one or more functions.

Table 3.4: Function-to-component mapping.

Function	Function Description	Performed by
MUMT.Func	Perform MUM-T Strike	MUM-T (strike) package
MUMT.Func.1	Execute C2	Manned fighter
MUMT.Func.1.1	Provide battlespace awareness	Manned fighter
MUMT.Func.1.2	Exercise positive control	Manned fighter
MUMT.Func.1.3	Exercise command	Manned fighter

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Table 3.4 – *Continued from previous page*

Function	**Function Description**	**Performed by**
MUMT.Func.2	Assess threats	Intelligence team
MUMT.Func.2.1	Receive intelligence	Intelligence team
MUMT.Func.2.2	Process intelligence	Intelligence team
MUMT.Func.2.3	Classify intelligence	Intelligence team
MUMT.Func.2.4	Disseminate intelligence	Intelligence team
MUMT.Func.3	Form team	MUM-T (strike) package
MUMT.Func.3.1	Monitor frequency	MUM-T (strike) package
MUMT.Func.3.2	Perform IFF	MUM-T (strike) package
MUMT.Func.3.3	Establish communications	MUM-T (strike) package
MUMT.Func.4	Generate assets	Launch platforms
MUMT.Func.4.1	Load threat data	Launch platforms
MUMT.Func.4.2	Refuel aircraft	Launch platforms
MUMT.Func.4.3	Re-arm aircraft	Launch platforms
MUMT.Func.4.4	Pre-flight aircraft	Launch platforms
MUMT.Func.5	Plan mission	Joint mission-planning team
MUMT.Func.5.1	Review orders	Joint mission-planning team
MUMT.Func.5.2	Review intelligence	Joint mission-planning team
MUMT.Func.5.3	Forecast weather	Joint mission-planning team
MUMT.Func.5.4	Generate targets	Joint mission-planning team
MUMT.Func.5.5	Determine assets	Joint mission-planning team
MUMT.Func.5.6	Determine weapons	Joint mission-planning team
MUMT.Func.5.7	Deteremine personnel	Joint mission-planning team
MUMT.Func.5.8	Assign targets	Joint mission-planning team
MUMT.Func.5.9	Generate plan	Joint mission-planning team
MUMT.Func.6	Service target	MUM-T (strike) package
MUMT.Func.6.1	Find target	Unmanned aircraft
MUMT.Func.6.2	Fix target	Unmanned aircraft
MUMT.Func.6.3	Track target	Unmanned aircraft
MUMT.Func.6.4	Target target	Unmanned aircraft

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Table 3.4 – *Continued from previous page*

Function	**Function Description**	**Performed by**
MUMT.Func.6.5	Engage target	MUM-T (strike) package
MUMT.Func.6.6	Assess effects	Unmanned aircraft
MUMT.Func.7	Transit assets	MUM-T (strike) package
MUMT.Func.7.1	Navigate assets	MUM-T (strike) package
MUMT.Func.7.2	Provide thrust	MUM-T (strike) package
MUMT.Func.7.3	Maneuver assets	MUM-T (strike) package

CHAPTER 4:
Simulation Models

This chapter discusses the models developed in this study. All models are developed in ExtendSim 9.0 simulation software. SAS Institute Inc.'s JMP Pro 10 and Microsoft's Excel are used for analysis of results. The chapter first describes the approach, assumptions and considerations used in developing the models. The chapter then describes the models developed and use for the DRM and analysis.

4.1 Modeling Approach

A kill chain is fundamentally a series of processes, that when executed successfully in the prescribed sequence, leads to the destruction of a objective or target. ExtendSim 9.0 is a simulation program that can be used for modeling discrete event processes. ExtendSim allows the modeling of simulation items that are generated and processed by discrete activities as the items travel through the model along a defined path. Activity blocks along the path simulate the performance of service or impose delays on the items. Attributes can be assigned to each simulation item to facilitate the understanding of the behavior and traits of the item as it moves through the model.

4.2 Measures of Effectiveness

The efficiency of the kill chain process can be measured by the time it takes to complete the entire process. The faster the entire kill chain is executed, the less time the assets are exposed to danger. A shorter execution time also translates into a higher sortie generation rate. Thus, to evaluate the effectiveness of the MUM-T (strike) for the design reference mission, the following measure of effectiveness (MOE) are used. They are described in the following paragraphs.

1. Total Mission Time
2. Mission Time
3. RV Time

4.2.1 Total Mission Time

This MOE measures the efficiency of the entire strike force, including those elements within the expanded kill chain. The mission completion time is calculated as:

Total Mission Time *= Force Generation Time + Transition to Rendezvous Point Time + Airborne Link Up Time + Ingress Time + F2T2E Cycle Time + Egress Time*

Force Generation Time – This refers to the time to generate the necessary assets for the mission. It includes the generation of fighters and UCAVs and is measured from the time an asset is assigned for the mission to the time the asset takes off for the mission.

Transition to Rendezvous Point Time – This refers to the time it takes the assets to transit from the launch platform to the rendezvous point. It is dependent on the distance between the launch platform and the rendezvous point and the cruising speed of the asset. For this study, a rendezvous point that is equally distance from both launch platform is assumed for each simulation run. It is measured from the time the asset takes off to the time it reaches the rendezvous point.

Airborne Link-up Time – This refers to the time it takes for the entire MUM-T (strike) package to be formed. Recall that, for the purpose of this study, a MUM-T (strike) package consists of four MUM-T (strike) units of a fighter paired with two UCAVs. Should a fighter reach the rendezvous point before two UCAVs are available for link-up, the fighter is assumed to be hold at the rendezvous point and await the arrival of two UCAVs before the link up is performed. The time is measured from the time the first fighter or UCAV takes off to the time the MUM-T (strike) package is formed.

Ingress / Egress Time – This is the time it takes for the MUM-T (strike) package to ingress and egress from the rendezvous point to the area of operations. For the purpose of this study, it is assumed that both the ingress and egress distance is the same. The time necessary for evasive actions to counter adversary counter-air is assumed to be zero.

"Find, Fix, Track, Target, Engage" Cycle Time This is the time it takes the UCAVs to find, fix, track, target and engage the assigned targets.

4.2.2 Mission Time

This MOE measures the airborne time required to perform the mission. It includes the time to transit to the rendezvous point, the time to form the MUM-T (strike) package, the time to cycle through the kill chain and both the time for the package to ingress and egress. The Mission Time is calculated as:

Mission Time *= Transition to Rendezvous Point Time + Airborne Link Up Time + Ingress Time + F2T2E Cycle Time + Egress Time*

The reason for specifically breaking out Mission Time is to reveal the amount of time the aircraft are required to be airborne. As the manned fighters have a limited endurance of about two hours, the airborne time is critical to the successful completion of the strike operation.

4.2.3 Rendezvous (RV) Time

The RV Time is the time required to form up the MUM-T (strike) package consisting of four pairs of MUM-T teams. Each team consists of one manned fighter paired with, and having positive control of, two unmanned assets. The time is measured from the time the first asset (fighter or UCAV) arrives at the rendezvous point to the time the MUM-T (strike) package is formed. The RV time is calculated as:

RV Time *= (Time at Formation of MUM-T (strike) package) – (Time at First Aircraft Arrival at Rendezvous Point)*

Manned-unmanned teaming introduces the unique requirement to establish a communication and command data link to form the MUM-T (strike) package. Recall that in the mission definition described in Section 3.5, this is performed in the air at the rendezvous point. The RV Time enables the measurement of the time required to form strike package.

4.2.4 Measure of Performance

From the MOEs described above, the following MOPs are identified.

1. Airborne Link-up Time
2. F2T2E Cycle Time

3. Fighter Generation Time
4. UCAV Generation Time

Both the Fighter and UCAV Generation Times are broken down into the specific tasks necessary to generate a mission-capable asset. The decomposition includes:

1. Asset Re-Arm
2. Asset Pre-Flight
3. Asset EOR

4.3 System Description

The following paragraphs provide a brief description of the platforms described in the DRM.

4.3.1 F-35 Lightning II

The F-35 Lightning II is a fifth-generation VLO manned fighter. In its stealth configuration, the weapons are carried in the internal weapons bay. The F-35C is designed to operate from aircraft carriers. The F-35C has an endurance of just over two hours with two JDAMs and two air-to-air missiles. The F-35 Lightning II employs the electro-optic targeting system (EOTS) for target location, identification and designation. The EOTS can operate in both air-to-air and air-to-ground mode, and includes capabilities of long range infrared search and track (IRST) and laser designation and spot tracking functions. As the performance specifications of the EOTS are classified, a set of representative performance specifications is used for modeling. Table 4.1 shows the representative performance specifications used for modeling and the stage of the kill chain that the specification is applicable to. For the purpose of this study, it is assumed that the EOTS is also employed on the UCAV.

Table 4.1: EOTS specifications (representative) used for modeling

Description	Performance	Kill Chain Stage
Maximum Detection Range	60nm	Find
Maximum contacts of interest (COI) Detection	100	Find
Minimum Time to Detect	0.01	Find
Maximum Simultaneous Track	20	Fix, Track
Minimum Time to Fix Track	0.05	Fix, Track
Maximum Simultaneous Target	1	Target
Maximum Simultaneous Attack	1	Engage
Time to Engage	2 seconds	Engage

4.3.2 Unmanned Combat Aerial Vehicle - X-47X

The X-47X is a fictitious weaponized, stealth UCAV used in this study. The X-47X performance specifications is based largely on the X-47B. It has a projected weapons payload of 4,500 pounds. It possesses advanced LPI datalinks and is capable of airspeeds in excess of 400 knots. The X-47X can be embarked on an aircraft carrier or a CVEX 2 vessel. The X-47X is planned to be fielded beyond the 2020 time-frame. Figure 4.1 shows the specifications of the Northrop Grumman X-47B [31]. The figure also shows the relative size of the X-47B against the F/A-18E/F.

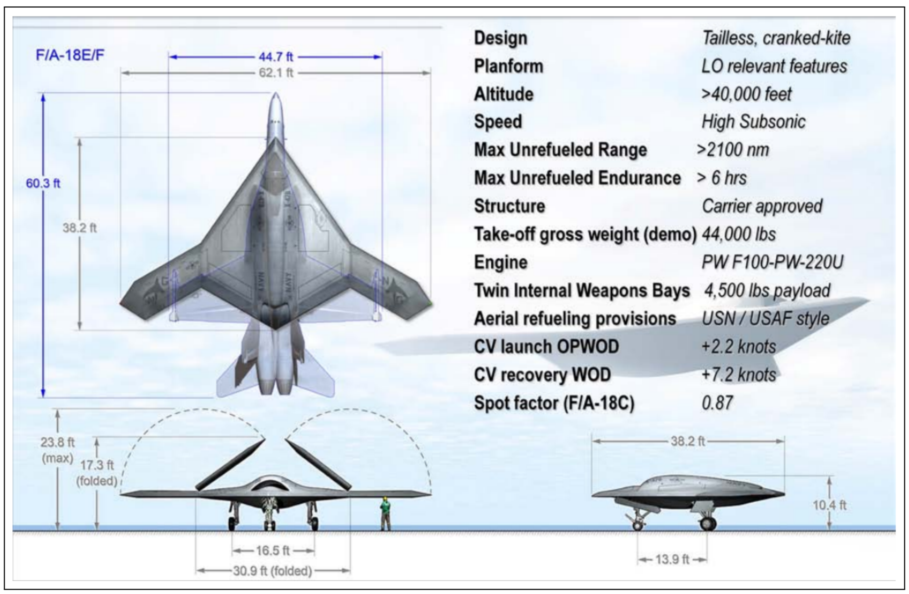


Figure 4.1: Nothtrop Grumman X-47B specifications [31].

4.3.3 GBU-39, Small Diameter Bomb

The GBU-39 SDB is a 250-pound class wing-bomb equipped with inertia navigation system (INS) and Global Positioning System (GPS) guidance system. It is suitable for servicing fixed and stationary targets, such as buildings, roads and parked aircraft. The bomb can be employed in all weather conditions and has a standoff range of up to 60nm. It uses its onboard INS and an anti-jam GPS to fly towards the target. Its accuracy is augmented by a differential GPS system, providing flight path corrections to enhance accuracy. The GBU-39 has a reported circular error probable (CEP) of 3 meters [32]. The GBU-39 is currently integrated with the F-15, but there are integration efforts for the GBU-39 to be employed by the F-35 and UCAV [33].

4.4 ExtendSim Model

For the initial study, two models are developed in ExtendSim 9.0. The first model addresses the processes for the USMC Kill Chain – F2T2E. The second model includes the additional activities of the expanded kill chain. Activities in the expanded kill chain include the activities associated with asset generation, airborne link-up, ingress and egress. For consistency, the following text style is applied to refer to the various elements in the simulation model.

- *Sentence case in italics* – ExtendSim simulation block type
- "*Italic Title Text in Parenthesis*" – Specific ExtendSim simulation block label

The basic processes of the kill chain is modeled using *Activity* blocks. Each target in the target list is represented as an "item" in the simulation. "Items" are generated by the *Create* block. A *Queue* block is used as a holding tank to hold the "items" in queue should the capacity of the *Activity* block be used up. A "First-in, First-out" queue policy is adopted for all *Queue* blocks. Each block contains specific parameters that can be defined to enable the modeling of specific system characteristics or performance specifications. Table 4.2 presents selected parameters of the blocks.

Table 4.2: ExtendSim modeling block parameters

Block Type	Parameters
Create	Creation Schedule, Number to Create
Activity	Capacity, Delay Time
Queue	Maximum Queue Length, Sort Policy, Renege Time Limit

4.4.1 Assumptions

The following assumptions are made for the model.

1. All detected COIs can be identified and classified. However, the maximum number of COIs that can be identified and classified depends on the sensor performance specifications.
2. Targeting system performance degradation as a result of atmospheric conditions are not considered.
3. All tracked targets are targeted. The capacity of targeting is determined by the system limitations.
4. The system is operating in air-to-ground (look down) with heavy ground clutter.
5. No defensive counter-air is encountered due to the covert ingress and detection avoidance actions employed by the UCAVs and with the manned fighters remaining outside the ADIZ.
6. The UCAV used in this study employs the same targeting system as the fighter.
7. There are no false alarms. All targets detected are legitimate and are an assigned target.
8. Each target is serviced by one weapon. Should the weapon not destroy the target, there will not be a subsequent attempt to service that target again.
9. All assets are refueled at the end of the last flight.
10. There is no degradation in the pilot's performance due to the increased workload of having to control two unmanned aircraft.
11. The triangular distribution is used to define the distribution of the cycle times for the activities in the kill chain.

4.5 Kill Chain Model

The first model is that of the USMC kill chain. This model enables us to determine the time required to execute the USMC kill chain. The times obtained are used as inputs for the second model, which models the expanded kill chain. In the expanded kill chain model (see Section 4.6), the USMC kill chain is modeled as a single activity block. The kill chain model is used to generate 500 simulation runs of the USMC kill chain. The outputs from this model are the mission success rate and the cycle time for the servicing of 64 targets through the kill chain. Targets are defined to appear according to a Poisson distribution with a λ of 0.5 seconds. The total targets assigned is equal to the weapons load out for the eight UCAV. Assuming each UCAV is capable of a 4,500 lbs payload. Each UCAV can carry 2 x 2,000 lbs JDAM or 8 x 250 lbs GBU-39 (SDB). To maximize target servicing, each UCAV has a weapons load out of 8 x SDBs, giving a total target servicing capacity of 64 targets.

For this model, the assumption is that the UCAVs ingress at a speed of 400 knots at an altitude of 30,000 feet. Targeting is performed in a look-down attitude with high ground clutter. Weather conditions is assumed to be ideal over the target. Figure 4.2 shows the envisaged profile used for the model. A straight-in approach towards the target is assumed.

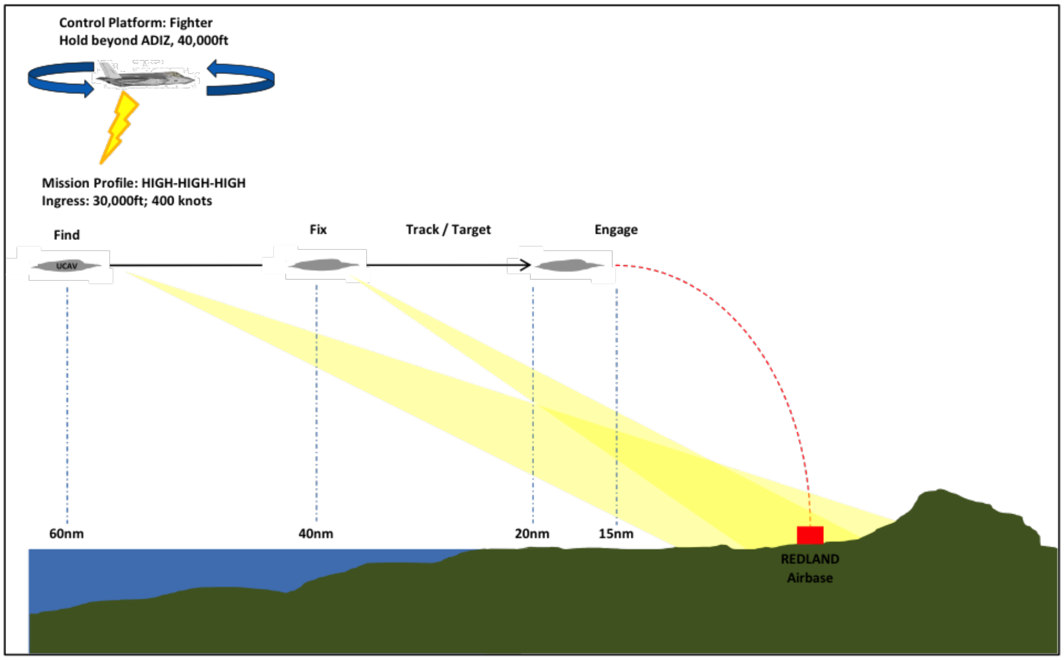


Figure 4.2: Profile used to determine modeling parameters, including spatial dimensions. This profile is used to determine the maximum allowable time for the completion of each activity in the kill chain. Maximum allowable time is based on distance away from target and ingress speed of the UCAV.

Find – The "Find" process is started at 60 nm out from expected target location and must complete by 40 nm. The "Find" process occurs concurrently as the UCAV ingress towards the target. Thus, the maximum time it has to find the target is three minutes. If the latitude and longitude of the target is known, the find is expected to take very little time (minimum of 0.5 minutes). It is assumed that it most likely takes the UCAV 1.5 minutes to find the target. A triangular distribution is assumed for this process. Based on the author's professional experience, a probability of detection of 0.90 is assigned for a scenario where the targeting system is at altitude, looking down with heavy ground clutter. Should the target not be detected by 40 nm from the target, the UCAV must execute a go-around and re-establish the strike profile setup. This is expected to take between 2.5 to 5 minutes, with a most likely time of 3 minutes. A triangular distribution is also assumed for this process.

Fix – Upon finding the target, the UCAV will "Fix" onto the target. Again, this process occurs concurrently as the UCAV ingress towards the target. The "Fix" must be completed within 20 nm from the target. Thus, the maximum time it has to fix the target is three

minutes. Once found, the fix is relatively quick, requiring a minimum of 1 second, and a most likely time of 5 seconds. A triangular distribution is assumed for this process.

Track and Target – When the target is fixed, the tracking continues and target solution is generated to determine the release point of the weapon. This must be completed by reaching 15 nm from the target. 15 nm is chosen as the SDB can be launched from 15 nm out. The maximum time available to track and target is 45 seconds. However, most tracking and targeting is done automatically in the system and the minimum time take is estimated to be 0.5 seconds, and a most likely time of 1 second.

Engage – Upon successful target solution generation, the engagement is performed with weapon release. This is accomplished by opening the weapons bay doors and releasing the weapon. This requires 2 seconds to open the door and release weapon. Although this is performed concurrently with the UCAV ingress towards the target, the time is accounted for towards the F2T2E timing.

Table 4.3 summarizes the distribution models used for the various operational activities in the kill chain. The *Queue* blocks have a renege function defined, ensuring that a target that stays in the *Queue* blocks beyond a specific amount of time leaves the queue and is counted as not targeted and consequently not destroyed. In such instances, these targets are considered to have "evaded" the kill chain. Targets that are not targeted, hit or killed as determined by the probabilities assigned are called "leakers" and are considered to have "leaked" through the kill chain. The probability of hit is calculated using the SDB's CEP of 3m against an adversary aircraft on ground of dimensions 13 m wingspan and 20 m length and assuming a Normal distribution for impacts.

Table 4.3: System specifications (representative) distributions used for modeling the kill chain.

Parameters	**Distribution Parameters**	**Remarks**
Go-Around Time [seconds]	Tri(90, 300, 180)	The time required to go-around and reset the strike approach.
Time to Fix Track [seconds]	Tri(1,180,5)	The time required to obtain a fix on a target once it has been located.
Time to Track and Target [seconds]	Tri(0.5,45,1)	The time required to track the target and generate a target solution.
Time to Engage [seconds]	Tri(1.5, 2.5, 2.0)	The time required to release the weapon upon weapon release command. This includes the opening of the weapon bay doors.
Probability of Detection	0.90	Probability that the target can be located. Assumes a look down approach with high ground clutter.
Probability of Target Solution	0.99	The probability that the target solution generated is accurate.
Probability of Hit	0.98	Probability that the weapon will hit the target.
Probability of Kill	0.85	Probability that the hit on the target will destroy the target.

4.5.1 "Find, Fix, Track, Target, Engage" Times

Figure 4.3 shows the model built in ExtendSim 9.0 for the USMC kill chain. This model is used to determine the mean F2T2E times to service each target. It is assumed that each UCAV is assigned a unique set of targets and is able to engage eight targets simultaneously. The model is set up to return the mean time it takes a target to be processed through the F2T2E kill chain. 500 simulation runs are conducted with the model and the mean target servicing times for each run obtained. JMP Pro 10 was used to determine the approximate distribution of the target servicing times. From the analysis (see Figure 4.4), the mean target servicing time follows a Normal distribution with mean 4.373 minutes and a standard deviation of 0.692 minutes.

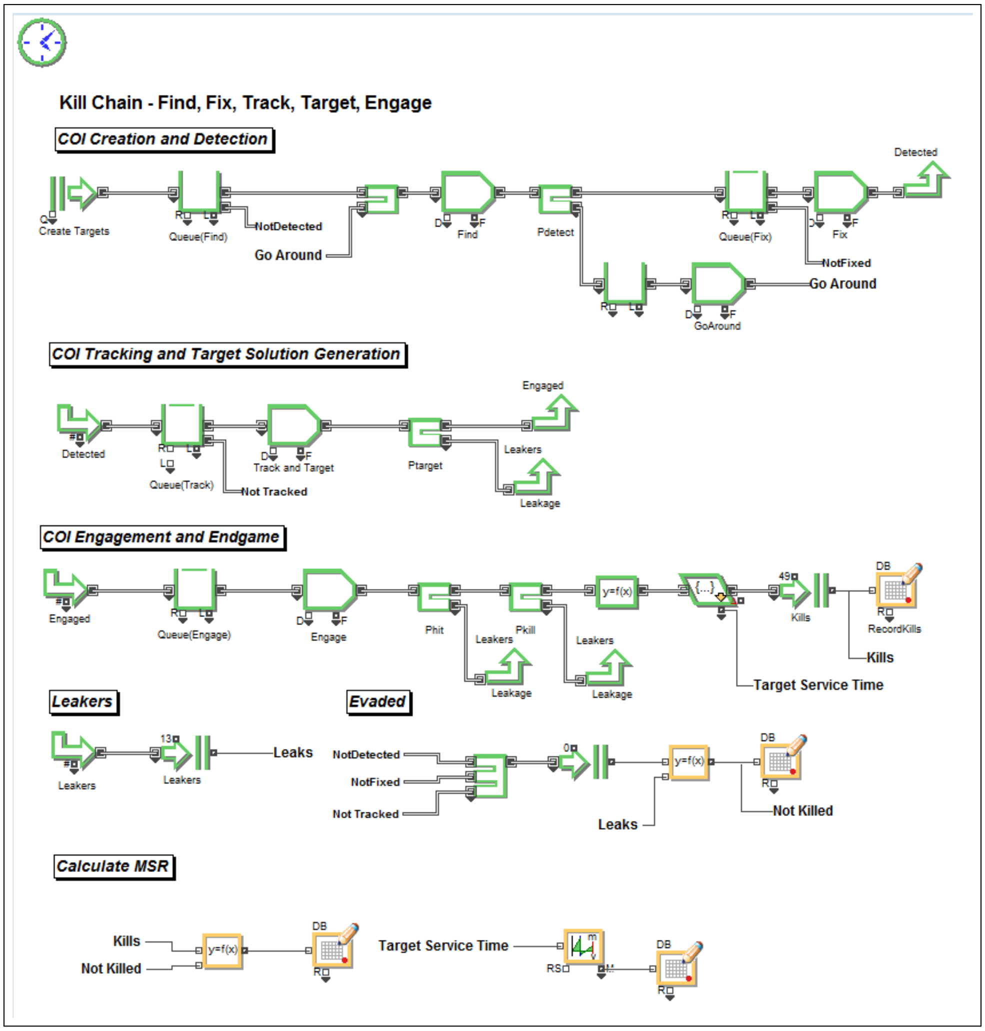
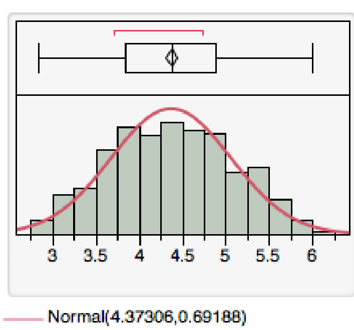


Figure 4.3: USMC kill chain modeled in ExtendSim. The model is segmented into three parts: Creation and detection, tracking and targeting, and engagement. Features are included to account for "leakers," targets that have "evaded" the kill chain, and the mission success rate.



Quantiles

100.0%	maximum	6.00261
99.5%		5.89382
97.5%		5.64513
90.0%		5.3274
75.0%	quartile	4.88211
50.0%	median	4.36999
25.0%	quartile	3.84878
10.0%		3.42371
2.5%		3.12334
0.5%		2.91094
0.0%	minimum	2.8329

Summary Statistics

Mean	4.3730602
Std Dev	0.6918849
Std Err Mean	0.030942
Upper 95% Mean	4.4338529
Lower 95% Mean	4.3122675
N	500

Figure 4.4: Determination of distribution for mean F2T2E time

4.5.2 Mission Success Rate

Figure 4.5 shows the distribution of the mission success rate (MSR) obtained for the 500 simulation runs.

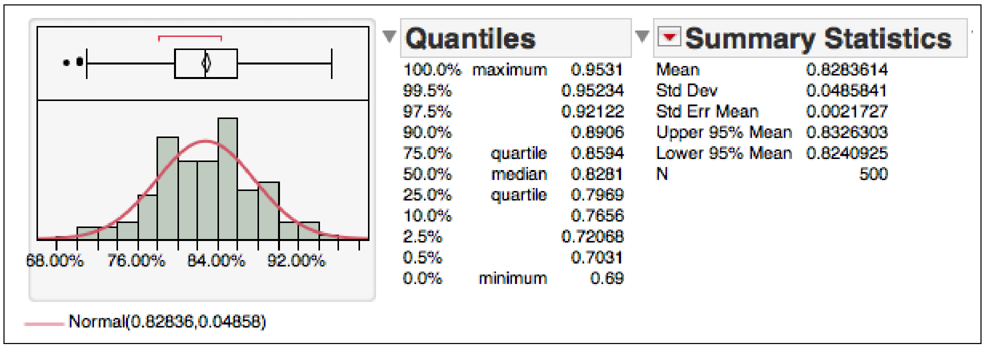


Figure 4.5: Distribution of mission success rate, including mean and standard deviation.

The MSR results for the USMC kill chain model is shown to have a mean of 82.84%. This is somewhat surprising given the high probability of hit and high probability of kill used in the model and consequently, a higher MSR was expected. The analysis found that while no targets were reneged from the queues, and all targets that appeared were eventually detected and serviced through the kill chain, there was a significant percentage of targets (17.16%) that leaked from the kill chain process. Recall that targets that are not targeted, hit or killed as determined by the probabilities assigned are called "leakers" and are considered to have "leaked" through the kill chain. These leaks occurred at the various stages where a probability function was applied to the outcome of the respective kill chain process. A sensitivity analysis is then performed to determine the effects these probabilities have on the MSR. Table 4.4 shows the factors and their respective ranges used to determine which had the highest effect on MSR.

Table 4.4: Factors and ranges for mission success rate analysis

Factor	Range
Probability of Detection	0.5 to 0.9
Probability of Target Solution	0.8 to 0.99
Probability of Hit	0.7 to 0.98
Probability of Kill	0.7 to 0.9

Figure 4.6 shows output from JMP Pro 10 on the main effects that each factor has on the mission success rate.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Probability of Target(0.8,0.99)	10.275	3.350709	3.07	0.0182*
Probability of Hit(0.7,0.98)	6.3883333	3.350709	1.91	0.0983
Probability of Kill(0.7,0.9)	4.97	3.350709	1.48	0.1816
Probability of Detection(0.5,0.9)	1.9566667	3.350709	0.58	0.5776

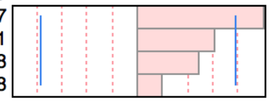


Figure 4.6: Effect analysis of factors for mission success rate

From Figure 4.6, it can be observed that amongst the factors, the "probability of target" factor has the largest effect on the mission success rate. The probabilities of detection, hit and kill had a lesser effect on the mission success rate. Based on the coefficient estimates for each factor, the effect on MSR from the "probability of target" factor is twice as large as that from the "probability of kill" factor, and approximately 1.5 times that from the "probability of hit" factor. It is of note that the probability of detection has little impact on the mission success rate. This was because there are TTPs in place in the model to reset the approach to ensure the detection of target and time required to perform the detection is within the time limit to detect the targets before detection is no longer possible because of the required engagement standoff range. It is also of note that whilst it is generally acknowledged that a high probability of hit and kill would guarantee a successful kill of a target, this simulation has shown that it may not necessarily be the case. The results suggest that the critical factor in mission success rate is the quality of the target solution generated.

Figure 4.7 shows the prediction profiles for the factors with maximum desirability. The desirability function in JMP Pro 10 enables the identification of the "best" or most desirable response achievable based the response function (maximize, minimize or target) and all factors. In this case, the response, MSR is to be maximized and the factors that provide the maximum desirability is derived using the desirability feature.

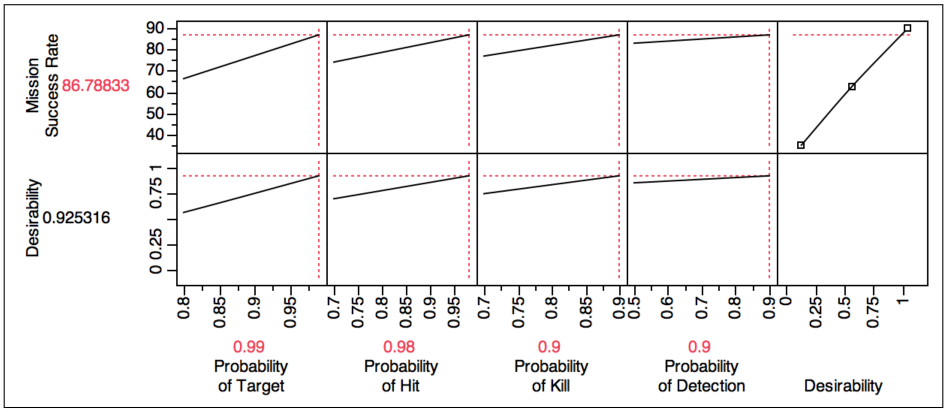


Figure 4.7: Predition profile for mission success rate for maximum desirability

With regard to maximizing desirability, Figure 4.7 shows the ideal values for each of the probabilities to maximize the mission success rate. It is of note that the upper bounds of these probabilities, for the purpose of this study, have been defined as very high. Even with the high probabilities, the maximum expected mission success rate is 86.79 percent. In reality, such high probabilities would be hard to achieve.

4.5.3 Insights from Kill Chain Model

The study of the F2T2E kill chain model has shown that while the weapon performance such as probability of hit and probability of kill has a direct effect on the mission success rate, the performance of the targeting system has the largest impact. A weapon's effectiveness is only as effective as the accuracy of the target information that it is supplied with. Of the five processes in the kill chain, four components, namely "find, fix, track and target," pertain specifically to the generation of an accurate target solution.

4.6 Baseline Expanded Kill Chain Model

The subsequent simulation model built is that for the baseline expanded kill chain. This simulation model takes the F2T2E kill chain and expands it to include the activities necessary to generate the aircraft (manned and unmanned) for the mission, the airborne link-up between the fighter and the UCAVs and the ingress and egress portion of the mission. The operational activities in this kill chain is shown in Figure 3.2. The additional operational activities include threat assessment, mission planning, manned and unmanned aircraft generation, transition to rendezvous point, airborne link-up between manned and unmanned

aircraft, ingress and egress, and return to base. Figure 4.8 shows the simulation model built in ExtendSim for the expanded kill chain.

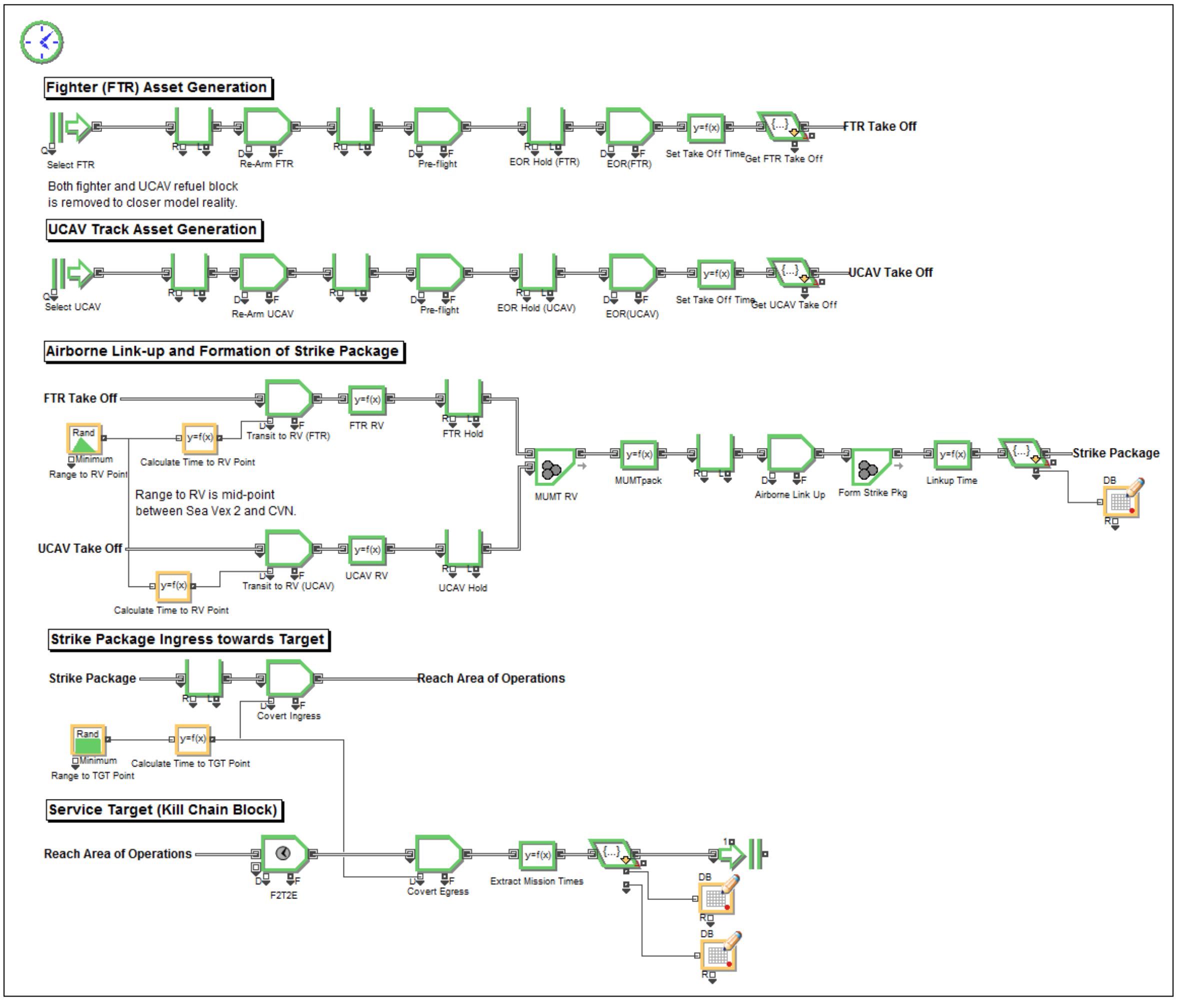


Figure 4.8: Expanded kill chain simulation model. This simulation model shows the five parts of the expanded kill chain, namely the two parallel processes in manned and unmanned aircraft generation, the formation of the MUM-T (strike) package, the ingress of the strike package towards the target, and the execution of the USMC kill chain and subsequent egress and return to base. Within the simulation model, information on the attributes of the simulation items are extracted and written to the database to determine the values of the measures of effectiveness.

The activity blocks and their respective parameters are modeled using open source performance specifications as well as the author's professional experiences. The study assumes that the period for the scenario (Section 3.2) is in the 202X timeframe. The F-35 Joint Strike Fighter (JSF) is used as the manned fighter in the modeling. For the projected capa-

bilities of a UCLASS system, the X-47B is used as a representative system for the future UCAV platform.

4.6.1 Model Description

This model excludes the activities of threat assessment, mission planning and intelligence debrief because these do not directly impact the time taken to execute the mission from the manned and unmanned systems' perspective. Similarly, intelligence debrief is not included as it is a post-mission function. The expanded kill chain model is divided into three major parts. The parts are described in the following paragraphs.

Part 1 - Fighter (FTR) Asset Generation and UCAV Asset Generation

This part of the simulation model simulates the aircraft generation activities that are necessary to generate a mission-capable fighter or UCAV. The simulation includes the process of aircraft selection, weapons loading, fighter and UCAV pre-flight inspections, and fighter and UCAV EOR inspections. Figure 4.9 Figure 4.10 show the simulation model for manned fighter and UCAV generation respectively. The details of each block are described in the following paragraphs.

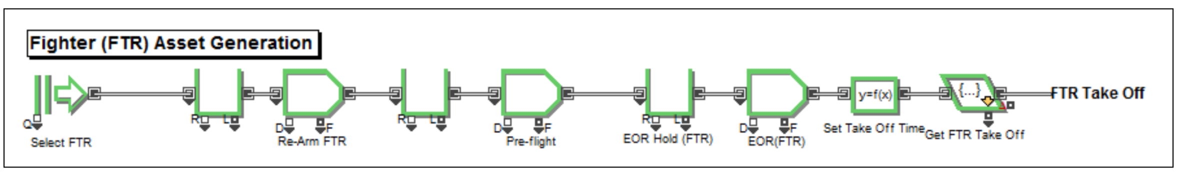


Figure 4.9: Fighter asset generation simulation model. These simulation blocks simulate the fighter aircraft generation process and includes the re-arming of the fighter aircraft, the pre-flight inspection that is performed and the end-of-runway inspection prior to the fighter aircraft taking off.

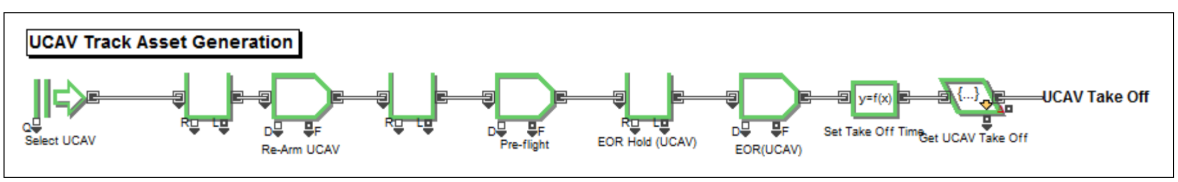


Figure 4.10: UCAV asset generation simulation model. These simulation blocks simulate the UCAV generation process and includes the re-arming of the UCAV, the pre-flight inspection that is performed and the end-of-runway inspection prior to the UCAV aircraft taking off.

Select FTR and Select UCAV – The "*Select FTR*" block is used to model the fighter aircaft selection. An item (fighter aircraft or UCAV) is generated based on a random uniform integer distribution, Uniform(1,2).

Re-Arm FTR and Re-Arm UCAV – The "*Re-Arm FTR*" and "*Re-Arm UCAV*" blocks models the process of weapons loading for the selected fighter or UCAV respectively. A lognormal distribution for the re-arming time is used for both, with a specified minimum time to re-arm defined in the distribution.

Pre-flight – Once the fighter aircraft or UCAV is re-armed, it undergoes a pre-flight inspection ("*Pre-Flight*" blocks). The time required to perform the pre-flight check is also assumed to be lognormal with a specified minimum time to complete.

EOR(FTR) and EOR(UCAV) – Upon completion of pre-flight inspections, the fighter aircraft or UCAV undergoes an EOR inspection before it takes off, "*EOR(FTR)*" or "*EOR(UCAV)*" block. The process time for EOR checks is assumed to be lognormal with a specified minimum time to complete.

Queue blocks – *Queue* blocks are placed before every activity block to hold any items that is waiting to be processed by any of the activity process blocks.

Set Take Off Time – The *Equation* block 

, "*Set Take Off Time*," calculates the total time taken to generate one mission-capable asset for fighter asset generation track and the UCAV asset generation track. It is essentially the time at when the asset takes off. The *Get* blocks  enables the extraction of the calulcated take off time.

Part 2 - Airborne Link-up and Formation of Strike Package

Figure 4.11 shows model for the transit of assets to the rendezvous point and the subsequent establishment of communications and command link (link-up) between the fighters with the UCAVs to form MUM-T (strike) units. Upon the completion of link up of four MUM-T (strike) units, the MUM-T (strike) package is formed and proceeds to ingress.

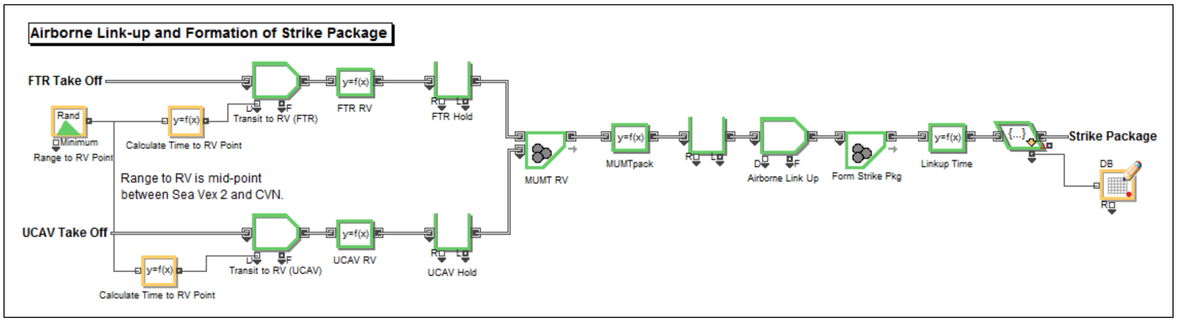


Figure 4.11: Airborne link-up and formation of strike package model

Forming the MUM-T (strike) Package – In the model, each fighter and UCAV is generated individually during the asset generation phase. However, upon take off and transit to the rendezvous point, the fighters and UCAV will link up and move through the model as a single item. The *Batch* block  is used to model the forming of MUM-T (strike) units consisting of one fighter teamed with two UCAVs. The conditions within the batching block is set to generate a new simulation item (MUM-T (strike) unit) when one fighter and two UCAVs arrive. The *Batch* block is again used to model the forming of a MUM-T (strike) Package consisting of four MUM-T (strike) units.

Part 3 - Ingress, "Find, Fix, Track, Target, Engage" and Egress

Figure 4.12 shows the model ingress, target engagment and egress of the strike package.

Covert Ingress – The time for the strike package to ingress depends on the distance between the rendezvous point and the target location. This distance is a randomly generated number, in nautical miles, using a uniform distribution, Uniform (200, 400) and serves as the input to the "*Covert Ingress*." The "*Covert Egress*" block uses the same generated number, in nautical miles. The strike package ingress speed is constrained to the slower of the cruise speeds between the fighter and UCAV. Recall that for this simulation, the cruise speed of the UCAV is slower and assumed to be 400 knots.

Find, Fix, Track, Target, Engage – Upon arriving at the target location, the process of"Find, Fix, Track, Target, Engage" is executed. The delay time to perform this is based on the distribution of the time to complete the kill chain. The distribution that was determined from Section 4.5 is used. Recall that the distribution for the USMC kill chain

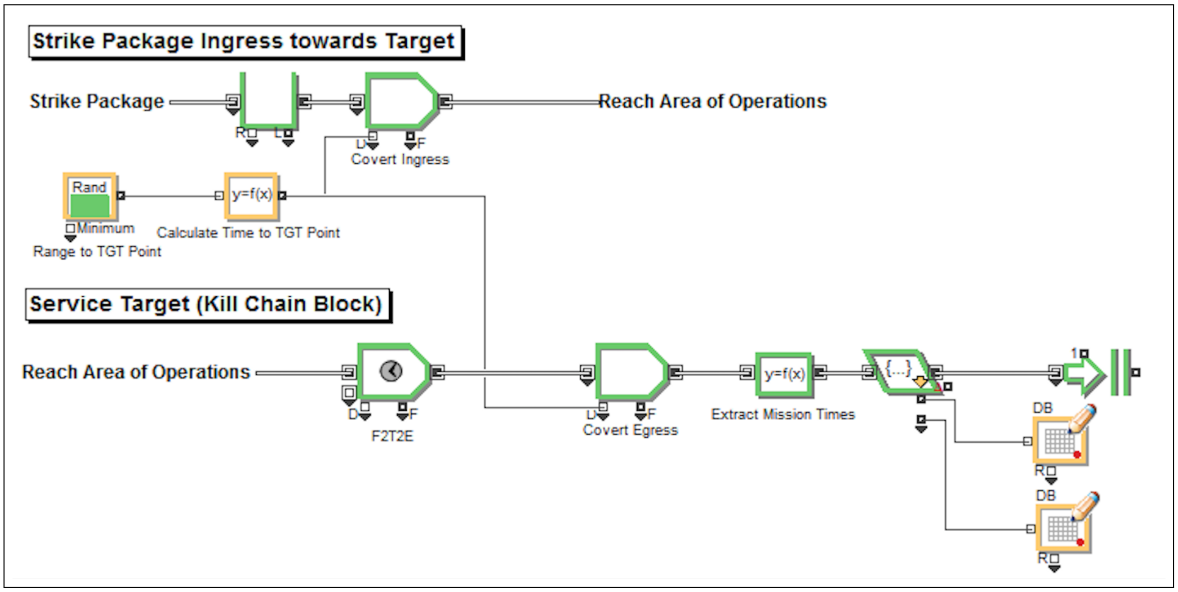


Figure 4.12: Strike package ingress, target engagement and strike package egress model

process is a Normal distribution with a mean of 4.373 minutes and a standard deviation of 0.0692 minutes.

Covert Egress – The time for the strike package to egress depends on the distance between the target location and the rendezvous point. For the purpose of this simulation, it is assumed that the distance to egress is the same as that for ingress. Recall that the number, in nautical miles, generated during the determination of ingress distance is used here as well. This ensures that the distance to cover during ingress between the rendezvous point and the target previously determined is consistent with the distance to cover during egress.

Extract Mission Times – The two Mission Times, Total Mission Time and Mission Time, is calculated in through the use of an *Equation* block  .

Get Block – This block facilitates the extraction of the calculated Mission Times.

Database Update – The extracted Mission Times are updated into the database for post-processing. This is performed using the *Database write* block  .

Exit Block – The *Exit* block  allows the simulation item to exit. The exit of the item also marks the end of one simulation run.

Table 4.5 summarizes the model parameters used in the expanded kill chain model. The ExtendSim block, as shown in Figure 4.8 previously, corresponding to the parameter is indicated in parenthesis.

Table 4.5: Summary of parameters in the expanded kill chain model.

PARAMETERS (EXTENDSIM BLOCK)
FIGHTER ASSET GENERATION
Re-arm fighters cycle time (Re-arm FTR)
Re-arming capacity (Re-arm FTR)
Pre-flight inspection of fighters cycle time (FTR Pre-flight)
Pre-flight inspection of fighters capacity (FTR Pre-flight)
Fighter End-of-Runway inspection cycle time (EOR(FTR))
Fighter End-of-Runway inspection capacity (EOR(FTR))
UCAV ASSET GENERATION
Re-arm UCAV cycle time (Re-arm UCAV)
Re-arming capacity (Re-arm UCAV)
Pre-flight inspection of UCAV cycle time (UCAV Pre-flight)
Pre-flight inspection of UCAV capacity (UCAV Pre-flight)
UCAV End-of-Runway inspection cycle time (EOR(UCAV))
UCAV End-of-Runway inspection capacity (EOR(UCAV))
AIRBORNE LINK-UP AND FORMATION OF STRIKE PACKAGE
Distance from launch platforms to rendezvous point (Range to RV Point)
Time for fighter to transit to rendezvous point (Transit to RV (FTR))
Time for UCAV to transit to rendezvous point (Transit to RV (UCAV))
Criteria to form MUM-T (strike) unit (MUMT RV)
Airborne data and command link-up cycle time (Airborne Link-up)

Table 4.5 – *Continued from previous page*

Parameters (ExtendSim Block)
Criteria to form MUM-T (strike) package (Form Strike Pkg)
STRIKE PACKAGE INGRESS TOWARDS TARGET
Distance from rendezvous point to target (Range to TGT Point)
Time to ingress from rendezvous point to target (Covert Ingress)
SERVICE TARGET
Time to execute "F2T2E" kill chain (F2T2E)
Time to egress from target to rendezvous point (Covert Egress)

4.6.2 Model Factors

JMP Pro 10 was used to develop the factorial combinations for the model. Three responses and nine factors were used. The first eight factors applies to asset generation times, while the ninth, airborne link up cycle time, applies to the MUM-T (strike) package formation time. For the purpose of modeling, the lower and upper bound of each factor was used. The factors used are described in Table 4.6. A fractional factorial design approach was used to generate the combinations. From this, a total of 64 combinations are generated. One hundred simulation runs is conducted for each combination, giving a total of 6,400 runs. One hundred runs is used to provide a sufficiently large enough sample size to estimate to obtain an asymptotically normal estimator of the mean values of the factors. For each combination, the mean of the Total Mission Time, Mission Time and RV Time is recorded.

Table 4.6: Design of experiment factors.

Response	Goal	
Total Mission Time	Minimize	
Mission Time	Minimize	
Airborne Link Up Time	Minimize	
Factor	**Lower Bound**	**Upper Bound**
Fighter Re-Arm	35 mins	45 mins
Fighter Pre-Flight	30 mins	50 mins
Fighter EOR	3 mins	10 mins
UCAV Re-Arm	30 mins	50 mins
UCAV Pre-Flight	10 mins	30 mins
UCAV EOR	3 mins	10 mins
Airborne Link Up Cycle Time	1 min	10 mins

4.7 Results Analysis

The analysis methodology and results from the simulation runs are discussed in this section.

4.7.1 Analysis Methodology

The results from the simulation runs of the 64 combinations are then analyzed in JMP Pro 10 to identify the factors that provided the most impact on the main effects. First, the effects analysis is performed to identify the factors and interactions with the largest effect. Next, the desirability function is used to determine the values of the factors that provide the most desirable response behavior. For this study, only the main effects are studied. Therefore, two or more factor interactions are ignored and pooled. The values are then used as the baseline factor parameter settings in the analysis of alternatives.

4.7.2 Total Mission Time

Figure 4.13 shows the factors, including interactions between the factors, that had the largest effect on the Total Mission Time. Ignoring two or more factor interactions, it is observed that the Fighter Pre-flight, Fighter and UCAV Re-arm are the top three factors had the highest main effects on the Total Mission Time.

Term	Estimate	Std Error	t Ratio	Prob>|t|
FTR Pre-Flt(30,50)	15.037187	0.211575	71.07	<.0001*
UCAV Re-Arm(30,50)	11.637813	0.211575	55.01	<.0001*
FTR Pre-Flt*UCAV Re-Arm	-8.809687	0.211575	-41.64	<.0001*
FTR Re-Arm(35,45)	6.9759375	0.211575	32.97	<.0001*
UCAV Re-Arm*FTR Re-Arm	-4.904688	0.211575	-23.18	<.0001*
Linkup TIme(1,10)	4.143125	0.211575	19.58	<.0001*
FTR Pre-Flt*UCAV Re-Arm*FTR Re-Arm	4.0065625	0.211575	18.94	<.0001*
UCAV Pre-Flt(10,30)	3.8115625	0.211575	18.02	<.0001*
UCAV Re-Arm*UCAV Pre-Flt	3.0984375	0.211575	14.64	<.0001*
FTR Pre-Flt*FTR Re-Arm	-2.567813	0.211575	-12.14	<.0001*
FTR Pre-Flt*UCAV Pre-Flt	-2.084063	0.211575	-9.85	<.0001*
FTR EOR(3,10)	1.9121875	0.211575	9.04	<.0001*
UCAV EOR(3,10)	1.47	0.211575	6.95	<.0001*
UCAV Re-Arm*UCAV EOR	1.444375	0.211575	6.83	<.0001*
FTR Pre-Flt*UCAV Re-Arm*UCAV Pre-Flt	-1.030937	0.211575	-4.87	<.0001*
FTR Pre-Flt*UCAV Re-Arm*UCAV EOR	-0.93125	0.211575	-4.40	<.0001*
FTR Pre-Flt*FTR EOR	0.8709375	0.211575	4.12	0.0002*
UCAV Re-Arm*FTR EOR	-0.729687	0.211575	-3.45	0.0013*
Linkup TIme*FTR EOR*UCAV EOR	-0.697188	0.211575	-3.30	0.0020*
FTR Pre-Flt*UCAV EOR	-0.631875	0.211575	-2.99	0.0047*
FTR Re-Arm*UCAV Pre-Flt	-0.612188	0.211575	-2.89	0.0061*
UCAV Re-Arm*FTR EOR*UCAV EOR	-0.46625	0.211575	-2.20	0.0332*

Figure 4.13: Effects analysis showing the factors with the largest effect on Total Mission Time. Only factors with significant effects (p-$value \leq 0.05$) are shown.)

Figure 4.14 shows the prediction profiler output for Total Mission Time. In this case, minimizing Total Mission Time achieves maximum desirability. The steepness of the prediction trace implies the factor's importance. As observed, the trace for Fighter Pre-flight factor has the steepest trace amongst the seven factors. The values for each of the seven factors that give the maximum desirability is shown (in red) in the figure. It is also interesting to note that both Fighter and UCAV EOR, and UCAV Pre-flight factors have no significant effect on the Total Mission Times. Marginal effects were also observed for the Linkup Time factor. The lowest predicted Total Mission Time is 276.15 minutes, or 4 hours and 36 minutes.

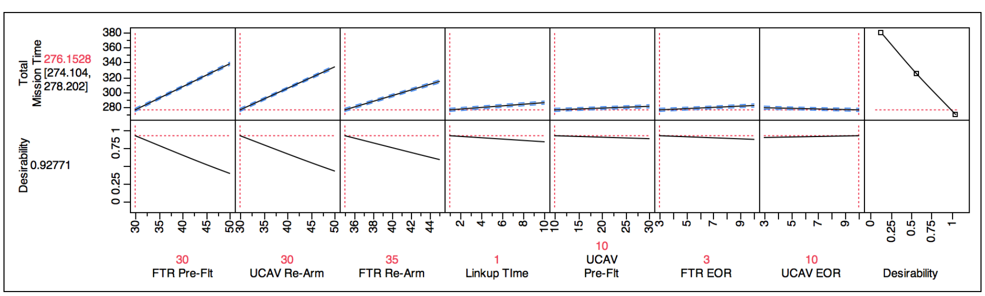


Figure 4.14: Prediction profiler for Total Mission Time with maximum desirability. Factors with the largest effect exhibit the steepest trace.

4.7.3 Mission Time

Figure 4.15 shows the factors, including the interactions between the factors, that had the largest effect on the Mission Time. Ignoring two or more factor interactions, it is observed that the Fighter Pre-flight, UCAV Re-arm, and Linkup Time factors are the top three factors with the highest main effects on the Mission Time.

Term	Estimate	Std Error	t Ratio	Prob>|t|
UCAV Re-Arm(30,50)	11.515313	0.201146	57.25	<.0001*
UCAV Re-Arm*FTR Pre-Flt	-8.849375	0.201146	-43.99	<.0001*
UCAV Re-Arm*FTR Re-Arm	-4.949063	0.201146	-24.60	<.0001*
FTR Pre-Flt(30,50)	4.93375	0.201146	24.53	<.0001*
Linkup TIme(1,10)	4.1184375	0.201146	20.47	<.0001*
UCAV Re-Arm*FTR Pre-Flt*FTR Re-Arm	4.0625	0.201146	20.20	<.0001*
UCAV Pre-Flt(10,30)	3.7371875	0.201146	18.58	<.0001*
UCAV Re-Arm*UCAV Pre-Flt	2.8596875	0.201146	14.22	<.0001*
FTR Pre-Flt*FTR Re-Arm	-2.40375	0.201146	-11.95	<.0001*
FTR Pre-Flt*UCAV Pre-Flt	-2.23625	0.201146	-11.12	<.0001*
FTR Re-Arm(35,45)	1.9378125	0.201146	9.63	<.0001*
UCAV EOR(3,10)	1.59125	0.201146	7.91	<.0001*
FTR EOR(3,10)	-1.509688	0.201146	-7.51	<.0001*
UCAV Re-Arm*UCAV EOR	1.480625	0.201146	7.36	<.0001*
UCAV Re-Arm*FTR Pre-Flt*UCAV Pre-Flt	-1.125625	0.201146	-5.60	<.0001*
FTR Pre-Flt*FTR EOR	0.88125	0.201146	4.38	<.0001*
UCAV Pre-Flt*FTR Re-Arm	-0.755938	0.201146	-3.76	0.0005*
UCAV Re-Arm*FTR Pre-Flt*UCAV EOR	-0.739063	0.201146	-3.67	0.0007*
UCAV Re-Arm*FTR EOR	-0.700313	0.201146	-3.48	0.0012*
FTR Pre-Flt*UCAV EOR	-0.636563	0.201146	-3.16	0.0030*
Linkup TIme*UCAV EOR*FTR EOR	-0.628125	0.201146	-3.12	0.0033*
UCAV EOR*FTR EOR	-0.514375	0.201146	-2.56	0.0144*
UCAV Re-Arm*FTR Pre-Flt*FTR EOR	0.47875	0.201146	2.38	0.0222*

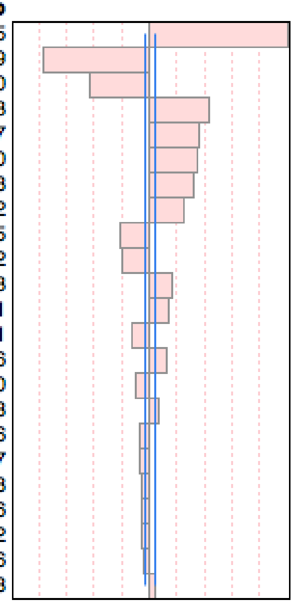


Figure 4.15: Effects analysis of factors for Mission Time. Only factors with significant effects (*p-value* ≤ 0.05) are shown.)

Recall that Mission Time measures the time that the assets are airborne. From the results, the two of the three factors that had the greatest impact on the Mission Times are the activities on ground and performed prior to the aircraft taking off. The factors with large main effects are:

1. UCAV Re-Arm (Re-arming of UCAV)
2. FTR Pre-Flt (Pre-flight inspection of manned fighter)
3. Linkup Time (Establishment of communications and command link up between one UCAV and one manned fighter)

This points to one interesting insight – that in missions where assets are generated from

different launch platforms, synchronization of launches, and consequently the asset generation activities, is critical in ensuring that the airborne rendezvous time is minimized.

Figure 4.16 shows the prediction profile output for Mission Time. As previously observed, UCAV and Fighter Re-arm and Fighter Pre-flight had significant effects on the Mission Time. Both Fighter and UCAV EOR had no effect on the Mission Time. It is also noted that, airborne link-up had little effect on Mission Time. The lowest predicted Mission Time for this scenario is 195.87 minutes, or 3 hours and 52 minutes.

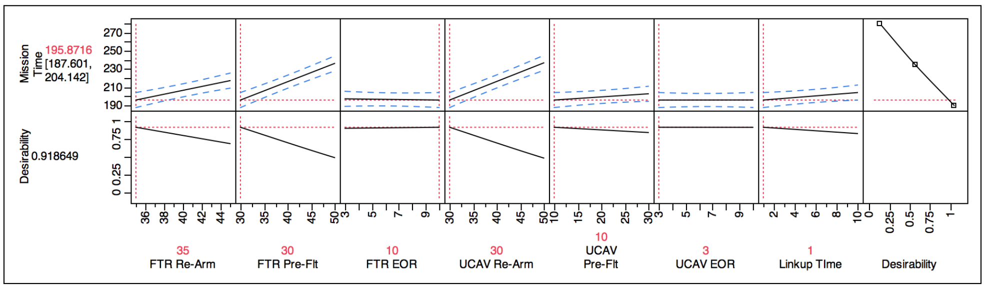


Figure 4.16: Prediction profiler for Mission Time with maximum desirability. Factors with the largest effect exhibit the steepest trace.

4.7.4 Rendezvous Time

Figure 4.17 shows the factors that has the largest effect on the RV Time. From the plot, it is observed that the Fighter Pre-flight, UCAV Re-arm and Linkup Time factors has the highest main effects on the RV Time.

Term	Estimate	Std Error	t Ratio	Prob>|t|
FTR Pre-Flt(30,50)	8.9023438	0.139137	63.98	<.0001*
UCAV Re-Arm(30,50)	8.0735938	0.139137	58.03	<.0001*
FTR Pre-Flt*UCAV Re-Arm	-6.868906	0.139137	-49.37	<.0001*
Linkup Time(1,10)	4.5279688	0.139137	32.54	<.0001*
UCAV Re-Arm*FTR Re-Arm	-3.945469	0.139137	-28.36	<.0001*
FTR Re-Arm(35,45)	3.8932813	0.139137	27.98	<.0001*
FTR Pre-Flt*UCAV Re-Arm*FTR Re-Arm	3.4907813	0.139137	25.09	<.0001*
FTR Pre-Flt*FTR Re-Arm	-3.131094	0.139137	-22.50	<.0001*
UCAV Re-Arm*UCAV Pre-Flt	0.9957812	0.139137	7.16	<.0001*
FTR Pre-Flt*UCAV Re-Arm*UCAV Pre-Flt	-0.669219	0.139137	-4.81	<.0001*
UCAV EOR*UCAV Pre-Flt	-0.664219	0.139137	-4.77	<.0001*
UCAV Re-Arm*UCAV EOR	0.4998438	0.139137	3.59	0.0008*
Linkup Time*UCAV EOR*FTR EOR	-0.435156	0.139137	-3.13	0.0031*
FTR Pre-Flt*UCAV EOR*FTR EOR	-0.418906	0.139137	-3.01	0.0042*
FTR Pre-Flt*UCAV EOR*UCAV Pre-Flt	0.3982813	0.139137	2.86	0.0063*
FTR Re-Arm*UCAV Pre-Flt	0.3360937	0.139137	2.42	0.0197*
UCAV Re-Arm*FTR EOR	-0.329531	0.139137	-2.37	0.0221*

Figure 4.17: Effects analysis showing the factors with the largest main effects on RV Time. Only factors with significant effects (*p-value* $\leq$ 0.05) are shown.)

Figure 4.18 shows the prediction profiler output for RV Time. Similar to the plots for the afore-mentioned MOEs, the steepness of the prediction trace implies the factor's importance. As observed, the trace for "FTR Pre-Flt" and "UCAV Re-Arm" appear to have the steepest trace amongst the seven factors. Unlike the prediction profile plots for the other MOEs, two of the traces in the prediction profile plot for RV Time exhibit a negative gradient. The trace for "UCAV Pre-Flt" and "UCAV EOR" factors exhibit an observable negative gradient, indicating that an increase in the cycle times for these two activities actually results in a reduction in the RV Time. The lowest predicted RV Time for this scenario is 116.46 minutes, or 1 hour 57 minutes.

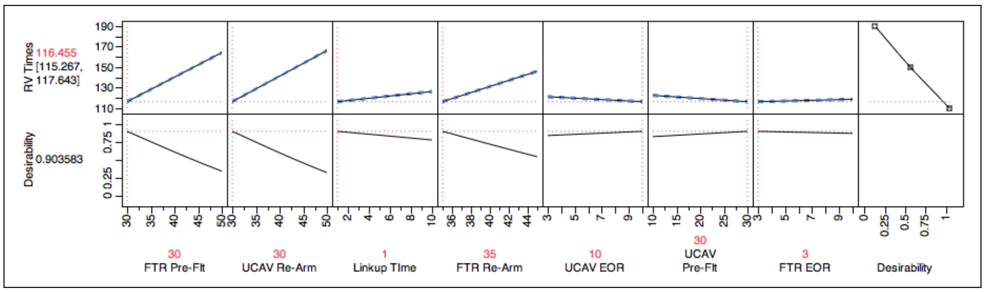


Figure 4.18: Prediction profiler for RV Time with maximum desirability. Factors with the largest effect exhibit the steepest trace.

4.8 Summary of Effects

Table 4.7 shows the top three factors with the highest main effects for the respective MOEs.

Table 4.7: Summary of factors with the highest main effects on MOE.

Measure of Effectiveness	**Factors with Largest Main Effects**
Total Mission Time	Fighter pre-flight inspection UCAV re-arming Fighter re-arming
Mission Time	UCAV re-arming Fighter pre-flight inspection Airborne link-up time
RV Time	Fighter pre-flight inspection UCAV re-arming Airborne link-up time

The table shows that there are common factors that have a large effect on all three MOEs. For manned aircraft, the pre-flight inspection and re-arming cycle times are the factors with the largest main effects. For unmanned aircraft, the re-arming cycle time has the largest main effect. The establishment of data and command link-up between manned and unmanned aircraft also has a significant effect on the MOEs that include airborne time as one of its factors, namely Mission Time and RV Time.

4.9 Insights from Expanded Kill Chain Model

Recall that Total Mission Time is the time elapsed from the time the asset generation begins to the time the strike package completes its egress and returns to the launch platforms. The results demonstrate that the efficiency in asset generation has a significant effect on the Total Mission Time. The results highlights the overall time required for the conduct of the strike operation. This information will enable mission planners to plan aircraft assignments and aircraft generation activities more effectively to support multiple MUM-T (strike) operations. In this scenario, with a mean Total Mission Time of 4 hours 36 minutes, the implication is that a maximum of three such strike operations can be executed in a twenty-four hour window

Further, the results from the expanded kill chain model suggests that the limiting factor in a MUM-T (strike) lies in the airborne formation of the MUM-T (strike) package. From the simulation, either the fighter or the UCAV holding at the rendezvous point spends a significant amount of time. In the simulation for the baseline expanded kill chain model, there is no attempt to synchronize the generation of manned and unmanned aircraft. As a result, if a manned aircraft reaches the rendezvous point first and there is no unmanned aircraft for it to establish the data and command link-up, the result is that the manned aircraft has to hold at the rendezvous point and wait for the arrival of the unmanned aircraft. These unsynchronized arrivals at the rendezvous points creates inefficiencies and also results in precious airborne time wasted by the manned aircraft holding at the rendezvous point. The following chapter proposes three alternatives. The alternatives proposed either aim to extend the endurance of the manned fighters or explore ways to minimize the Mission Time through synchronization or changes in the activity sequence in the expanded kill chain.

The next chapter explores the various alternatives that could reduce the expected RV Times

or increase the fighter's endurance to meet the required RV Times.

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CHAPTER 5:
Analysis of Alternatives

Three alternatives are proposed in this study as possible solutions to enable the execution of the MUM-T (Strike) mission. The identified main limiting factor was the limited endurance of the fighters. The need for covert ingress precludes the carriage of external fuel tanks by the fighters. The proposed alternatives either strives to extend the endurance of the fighters or to maximize the effectiveness of the baseline endurance of the fighters. Each alternative is analyzed for its benefits and challenges. A Pugh matrix is used to identify the most feasible solution based on the results of this study.

5.1 Alternative 1 - Aerial Refueling Tanker Support

This alternative describes the provision of an airborne tanker at the rendezvous point to extend the endurance of the fighters. Figure 5.1 shows the OV-1 of a possible CONOPS for this alternative. The following paragraphs describe the CONOPS.

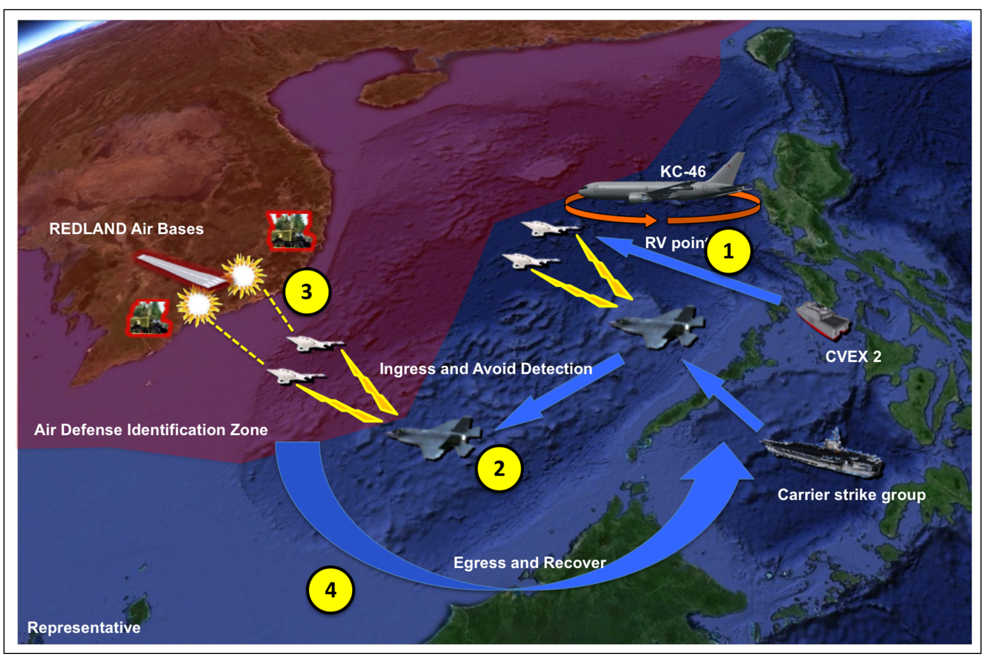

Figure 5.1: MUM-T (strike) operations with aerial refueling tanker support high-level operational view, OV-1. While largely similar to the baseline CONOPS, this CONOPS includes the use of an aerial refueling tanker to extend the endurance of the manned fighters.

Prior to the launch of the fighters or the UCAVs, an aerial refueling tanker aircraft, for example a KC-46, is prepositioned at the rendezvous point (1). The aerial refueling tanker aircraft provides the capability to increase the endurance of the fighters to maintain position at the rendezvous point while waiting for the form up of the MUM-T (strike) units. Upon successful formation of the MUM-T (strike) package, the package ingresses covertly towards the target (2). Meanwhile, the aerial refueling tanker will return to base. The UCAVs then enter the ADIZ and proceeds to engage the targets (3). Upon completion of the engagement, the package egresses covertly back to their respective recovery platforms.

5.1.1 Analysis of Alternative 1

One of the benefits of the MUM-T (strike) concept is the reduced exposure to threats to BLUELAND personnel while increasing the target servicing capacity of the BLUELAND strike force. While the use of aerial refueling tanker aircraft provides the benefits of extending the range and endurance of the fighters, and consequently the MUM-T (strike) package, this alternative also presents certain challenges and constraints.

First, the aerial refueling tanker aircraft is a high-value asset, thus it would have to be deployed to the rendezvous point with fighter escorts. This increases the resources required to carry out the strategic strike mission.

Second, although the aerial refueling tanker aircraft is stationed outside the REDLAND ADIZ, it would be still within range of REDLAND defensive counter-air. This puts the aerial refueling tanker aircraft at risk.

Third, the use of an aerial refueling tanker aircraft from the Air Force requires cross-service coordination, potentially increasing the mission planning and execution complexity. Close coordination will be required between the strike package launch platforms and the aerial refueling tanker aircraft launch platform to ensure that the on-station time for the tanker aircraft is optimized and to minimize the tanker aircraft's exposure.

Notwithstanding the above three concerns, it may be possible to employ unmanned carrier-launch airborne surveillance and strike as automated aerial refueling tankers to extend the endurance of manned fighters. A series of Defense Advanced Research Project Agency (DARPA) flight tests in 2012 successfully demonstrated the ability to safely conduct fully

autonomous in-flight refueling of UAVs at high-altitudes [34]. While the test utilized two Global Hawk aircraft flying in close formation (Figure 5.2) and was conducted to validate the concept of enabling UAVs to refuel autonomously in flight, the demonstration fuels the impetus for the concept to be extended to employing UCLASS in the role of autonomous aerial refueling tankers for manned fighters.

Figure 5.2: Two Global Hawks flying in close formation during DARPA's autonomous aerial refueling demonstration [34].

5.2 Alternative 2 - Synchronization of Asset Launch for "Just-In-Time" Arrivals

This alternative describes the synchronized launch of assets to minimize the difference in the assets' arrival times at the rendezvous point. The concept is akin to the "just-in-time" strategy developed by Toyota [35]. In that concept, the parts necessary for the assembly are delivered to the assembly plant just when they are required. This minimizes the warehousing requirements for the assembly plant drastically. When applied to the MUM-T concept, the synchronization of the launches for manned and unmanned aircraft can be managed such that the necessary types of aircraft arrive at the rendezvous point almost simultaneously. Consequently, the time required to hold at the rendezvous point to wait for the correct combination of assets to form the MUM-T (Strike) team is consequently minimized, too.

To analyze the effectiveness of this alternative, a modification to the expanded kill chain model is made. Keeping the parameters of all the model elements constant, changes are made to the *Create* block in the UCAV Asset Generation track. Instead of creating UCAV items according to a Poisson distribution, the UCAVs items are generated in two waves. Also, a delay is added to the UCAV generation to ensure that a UCAV item is only generated after a prescribed delay time. Operationally, this means that the UCAVs are provided with a different The specific hour on a specific dat at which a particular operation commences. (H-Hour), as compared to that for the fighters, in their mission orders. A range of delay times are explored. In addition to the delay, the number of items generated is also varied to study the effect it has on the RV Times. Table 5.1 shows the range in which the two factors are varied to determine the main effects.

Table 5.1: Factors and ranges for UCAV launch delay time effects analysis

Factor	**Factor range**
Launch delay time	10 to 120 mins
UCAVs launched in first wave	2 to 8

A full factorial design was used to generate the combinations of scenarios to run. Twenty-four combinations of delay times and number of UCAVs launched in the first wave was simulated. Each design point is repeated for one hundred simulation runs. Table 5.2 shows the twenty-four combinations.

Table 5.2: Alternative 2 – Twenty-four combinations for simulation, 100 simulation runs each.

Combination	**Launch delay**	**UCAV launched in 1st wave**
1	10	4
2	10	2
3	60	4
4	120	4
5	80	6

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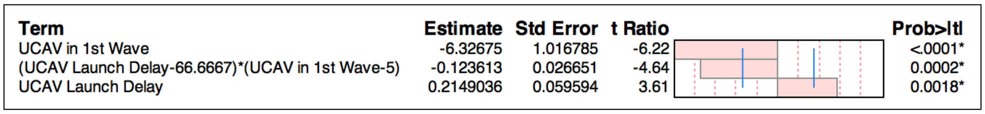
Table 5.2 – *Continued from previous page*

Combination	**Launch delay**	**UCAV launched in 1st wave**
6	60	8
7	30	4
8	120	8
9	30	6
10	100	2
11	80	8
12	120	6
13	30	8
14	60	6
15	100	8
16	120	2
17	10	8
18	10	6
19	100	6
20	80	2
21	100	4
22	80	4
23	30	2
24	60	2

The following figures present the results from the simulation runs. Figure 5.3 and Figure 5.4 shows the Pareto plot and effects plot for the two factors on RV Times, respectively. The Pareto plot also includes the effects from the interaction between the two factors. Figure 5.5 shows the effects from the interaction between the delay in UCAV launch and the number of UCAVs launched in the first wave.



Term	Estimate	Std Error	t Ratio	Prob>|t|
UCAV in 1st Wave	-6.32675	1.016785	-6.22	<.0001*
(UCAV Launch Delay-66.6667)*(UCAV in 1st Wave-5)	-0.123613	0.026651	-4.64	0.0002*
UCAV Launch Delay	0.2149036	0.059594	3.61	0.0018*

Figure 5.3: Pareto plot of factors on RV Times.

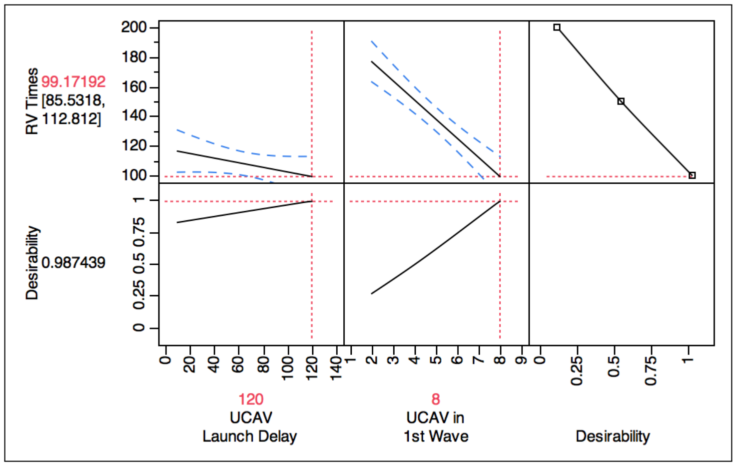


Figure 5.4: Effects analysis of factors on RV Times.

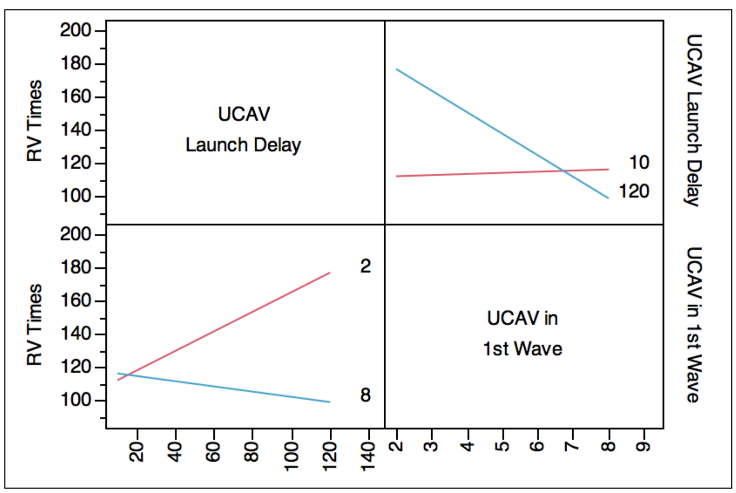


Figure 5.5: Prediction profiler for Mission Time with maximum desirability.

The results from the runs show that the number of UCAVs launched in the initial wave has the largest effect. The delay in launching UCAVs also has an effect on reducing the RV Times, but the magnitude of the effect is lower. A combination of increasing the number of UCAVs launched in the first wave and the delay in the launch of the UCAV serve to reduce the RV Times.

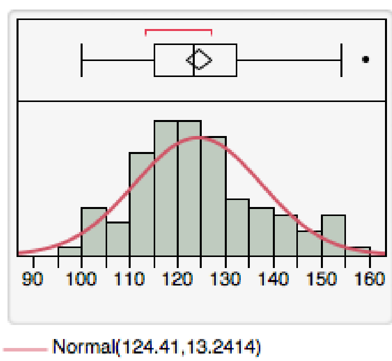
From the interaction plot, it is evident that interactions between the launch delay and the number of UCAVs launched in the first wave has a significant effect on the RV Times. The interaction plots are non-parallel, indicating that there interactions between the the two factors are significant. As observed from the interaction plots, increasing both the number of UCAVs launched and the delay in launching of the UCAVs results in a reduction in RV Times. Conversely, if the UCAVs initial launch is limited to only two assets, an increase in the delay time for launch has a consequence of increasing the RV Times. Thus, to maximize the effects on RV Times, a 120-minute delayed launch of 8 UCAVs is desired.

5.2.1 Analysis of Alternative 2

A modification of the expanded kill chain model was made to account for the delayed launch of the UCAVs. Specifically, the *Create* block for the UCAV asset generation track was changed to incorporate the delayed launch of the UCAV. For comparison, a simulation of the simultaneous launch of UCAVs was also performed. Both simulations are ran for simulation 100 runs and the mean RV Times obtained.

Simulation Results - RV Time

Figure 5.6 and Figure 5.7 shows the distribution of the RV Times obtained for the simultaneous launch of UCAVs and fighters (baseline model), and the delayed launch of the UCAVs respectively. In both cases, there is one outlier observed. Investigation of the data indicated that the outlier is a valid instance and the data point is retained for both cases.



Quantiles

100.0%	maximum	159.417
99.5%		159.417
97.5%		153.827
90.0%		144.348
75.0%	quartile	132.307
50.0%	median	123.287
25.0%	quartile	115.293
10.0%		107.841
2.5%		100.538
0.5%		99.8173
0.0%	minimum	99.8173

Summary Statistics

Mean	124.4102
Std Dev	13.241355
Std Err Mean	1.3241355
Upper 95% Mean	127.03757
Lower 95% Mean	121.78282
N	100

Figure 5.6: Distribution of RV Times for a baseline simultaneous launch of UCAV and fighters

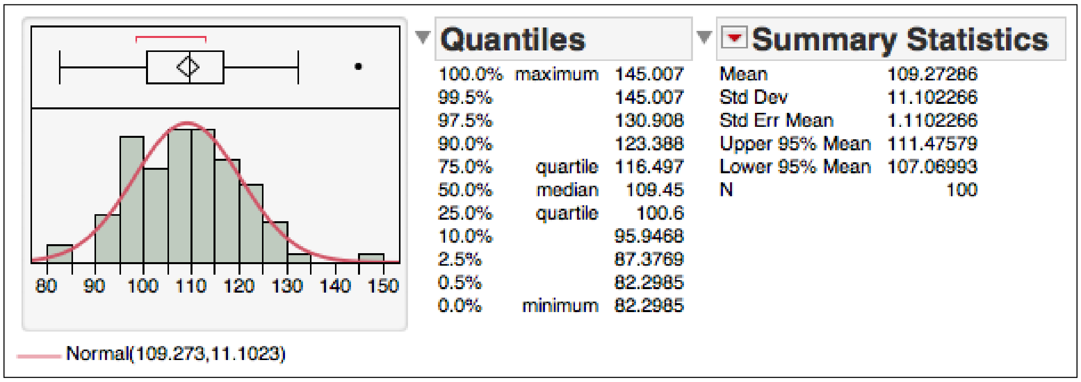


Figure 5.7: Distribution of RV Times for a 120 minutes delayed launch of 8 UCAVs

Hypothesis Testing of Means

A t-test for test of means, assuming unequal variances, is then performed to determine if there is a statistically significant decrease in the RV Times with the inclusion of a UCAV launch delay. The hypotheses are defined as follows.

$$\begin{aligned} H_o : &\quad \mu_{(baseline)} = \mu_{(UCAV\,delayed\,launch)} \\ H_{alternative} : &\quad \mu_{(baseline)} < \mu_{(UCAV\,delayed\,launch)} \end{aligned}$$

where:

$$\begin{aligned} \mu_{(baseline)} = &\quad \text{Mean RV Times for a simultaneous UCAV launch} \\ \mu_{(UCAV\,delayed\,launch)} = &\quad \text{Mean RV Times for a delayed UCAV launch} \end{aligned}$$

The t-test on the two sets of data is performed using JMP Pro 10 and also using the data analysis tool kit add-in in Microsoft Excel. A two-sample t-test assuming unequal variance is performed. Figure 5.8 shows the results of the t-test using JMP Pro 10. The results of the t-test using Microsoft Excel is shown in Table 5.3.

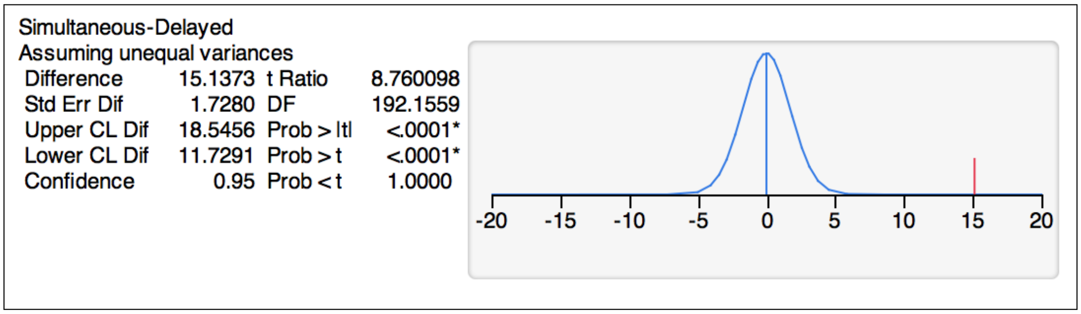


Figure 5.8: Results of two-sample assuming unequal variances t-test using JMP Pro 10. The red vertical line indicates the difference between the means of the RV Times, while the distribution indicates the areas where there is no statistically significant difference between the two means.

Table 5.3: Results of two-sample assuming unequal variances t-test using Microsoft Excel.

	$RV\ times_{(baseline)}$	$RV\ times_{(UCAV\ delayed\ launch)}$
Mean	124.41 mins	109.27 mins
Variance	175.33 mins	123.26mins
t Statistics	8.760	
P(T $\leq$ t) one-tail	5.08792×10^{-16}	

As observed from both t-test, the *p-value* is extremely small. Thus, there is sufficient evidence to reject the null hypothesis, H_o, that there is no difference in the mean RV Times for a simultaneous UCAV launch and a delayed UCAV launch at an α level of 0.05. This shows that there is a statistically significant difference between the RV Times for a simultaneous launch and the RV Times for a delayed UCAV launch. The delayed launching of the UCAV by 120 minutes and a launch of all 8 UCAVs in one wave has a statistically significant effect of reducing the RV Times.

While the study has shown that the simultaneous launch of eight UCAVs would be effective in reducing the RV Times, the physical limitations of launching eight UCAVs simultaneously from a CVEX 2 must be considered. The flight deck of a CVEX 2 is unlikely to be larger than that on the current aircraft carrier. This physically constrains the number of UCAVs that can be launched.

5.3 Alternative 3 - Pre-Launch Link-up

This alternative describes the establishment of data and command links (link-up) between the fighters and UCAVs before launch. In this alternative, the CONOPS require that each fighter perform link-up with two UCAVs as part of the asset generation process. Upon successful link-up, the fighters and UCAVs are then launched. This is expected to reduce the RV Times as well as the necessary airborne times for the assets. Figure 5.9 shows the high-level operational view of this alternative. The following paragraphs describes the sequence of operations.

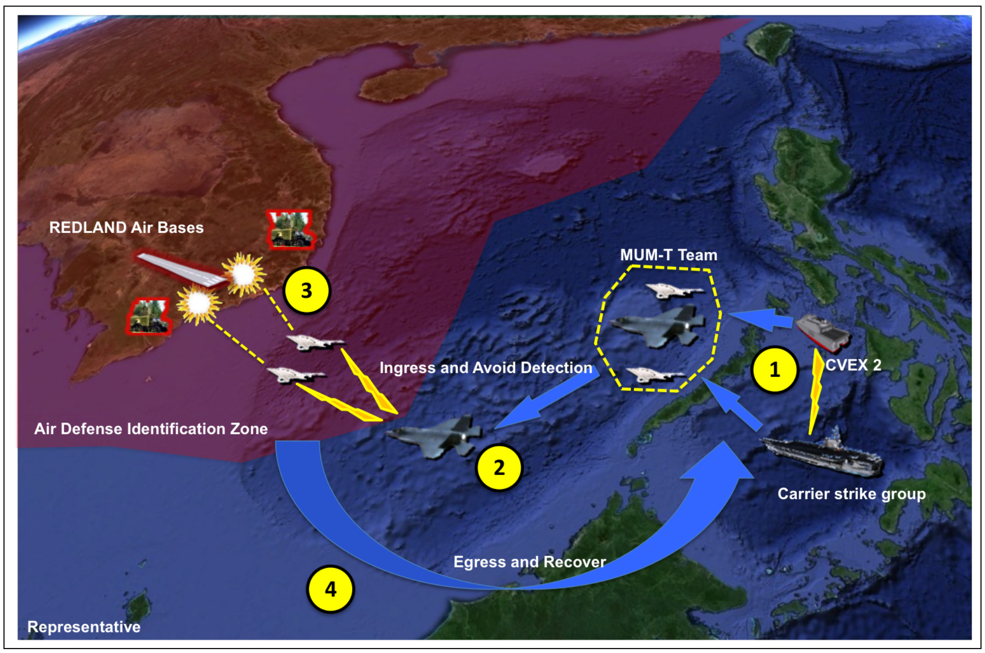


Figure 5.9: MUM-T (strike) with pre-launch link-up high level operational view

Prior to launch, the fighters onboard the aircraft carrier perform a coordinated establishment of data link and command link with the UCAVs on board the CVEX 2 (1). Upon successful link-up of the assets, the assets are simultaneously launched from both launch platforms and proceed to ingress covertly towards the ADIZ (2). The UCAVs continue into the ADIZ while the fighters, performing the role of an airborne command stations, remain outside the ADIZ. Upon reaching the targets, the UCAVs proceed to engage the targets (3). Upon completion of target engagement, the UCAVs then egress and vector towards the fighters outside the ADIZ. The package then returns to their respective recovery platforms (4).

5.3.1 Analysis of Alternative 3

While this alternative is expected to significantly reduce the RV Times, and consequently the airborne time of the assets, the aircraft carrier and CVEX 2 will likely need to be stationed close to each other to provide line of sight communications capability for the link-up. Under the distributed air wing concept, this is undesirable. The need to maintain this line of sight communications also places restrictions on the maneuverability of the aircraft carrier and the CVEX 2.

To analyze the effect this alternative has on the RV Time and the Mission Time, the expanded kill chain model is modified to include the establishment of data and command link prior to launching the assets. Figure 5.10 shows the modified ExtendSim model.

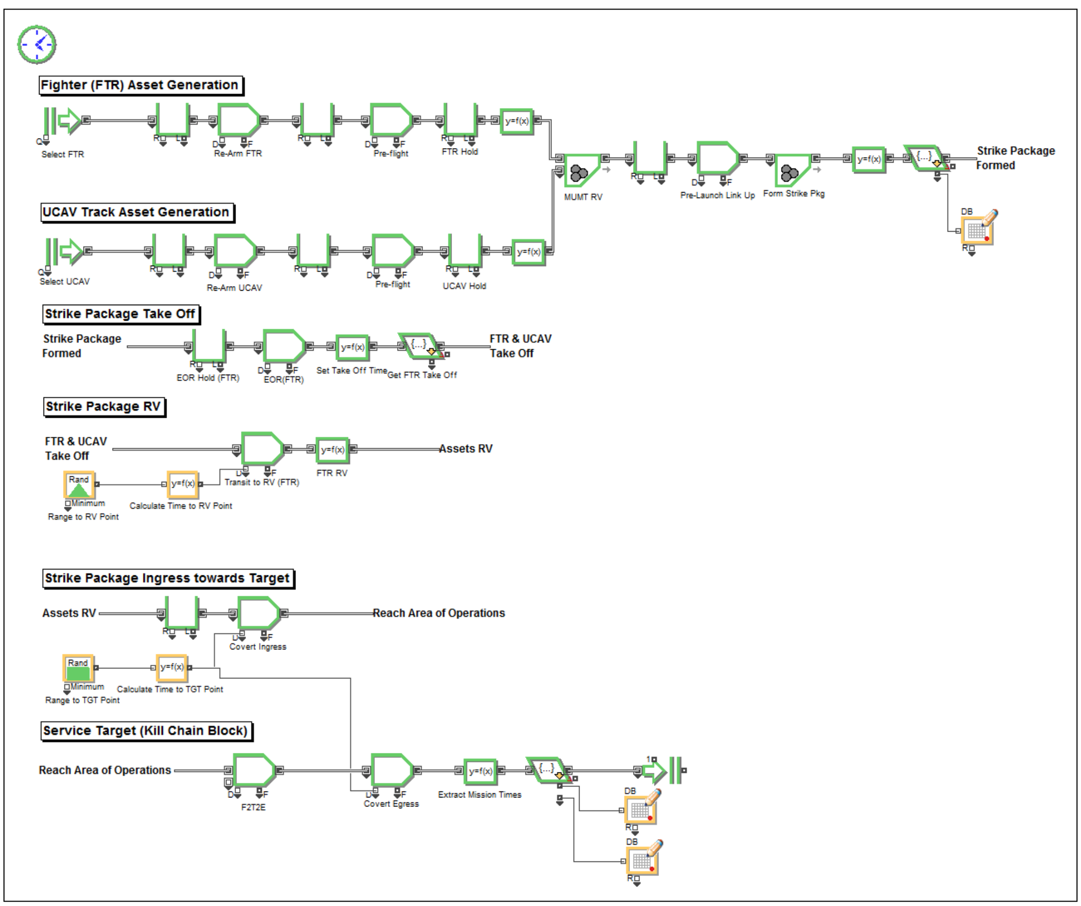


Figure 5.10: ExtendSim model for Alternative 3. Note the inclusion of the link-up processes prior to the EOR inspection and the launching of the assets.

The main difference of the model from the baseline expanded kill chain model is the moving of the MUM-T package formation from after asset takeoff to before EOR inspection. In this case, only after all assigned assets have completed the link-up would they be launched. This serves to minimize the time the assets are required to be airborne. However, the ingress and egress distance for the strike package is increased and includes the previously assumed distance from the launch platforms to the rendezvous point. All other parameters in the activity blocks remain consistent with that in the expanded kill chain model. For this alternative, the RV Time is calculated as the time the first asset is ready for link-up (simulation item reaches the “MUMT RV” block Figure 5.10)to the time the strike package is formed (simulation item exits the “Form Strike Pkg” block in Figure 5.10). One hundred simulation runs are made and the RV Time and Mission Time for each run is recorded.

RV Time

Figure 5.11 shows the distribution of RV Times obtained for Alternative 3. In the plot, three outliers are observed. Investigation of the data indicated that the outliers are valid cases and the data points are retained for the analysis.

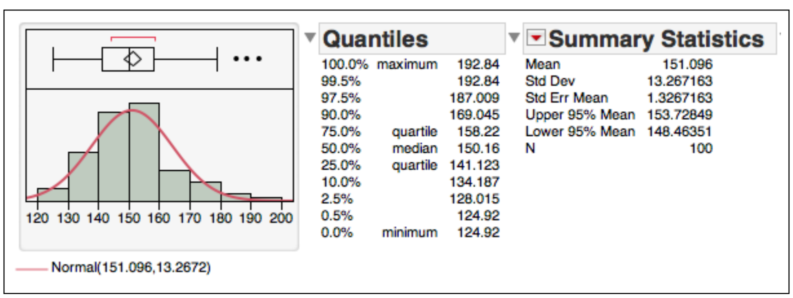


Figure 5.11: Distribution of RV Times for Alternative 3

The distribution for the RV Times for the baseline expanded kill chain model (Figure 5.6) shows an upper 95^{th} percentile of 127.04-minutes. We observe from the distribution of RV Times for Alternative 3, the mean of the RV Times is 151.10-minutes. As this is beyond the 95^{th} percentile of that for the baseline expanded kill chain model, it can be inferred that the pre-launch link-up CONOPs results in a longer RV Time when compared to the baseline expanded kill chain model. However, it is important to note that in Alternative 3, the link-up occurs while the assets are on the launch platforms; thus the previous limiting factor of fighter endurance will not be a constraint. In order to assess the effectiveness of

this alternative, an analysis of the Mission Time is performed. Recall that the Mission Time reveals the actual airborne time that is required of the assets.

Mission Time

Figure 5.12 and Figure 5.13 shows the distribution of Mission Times obtained for Alternative 3 and that from the baseline expanded kill chain model respectively.

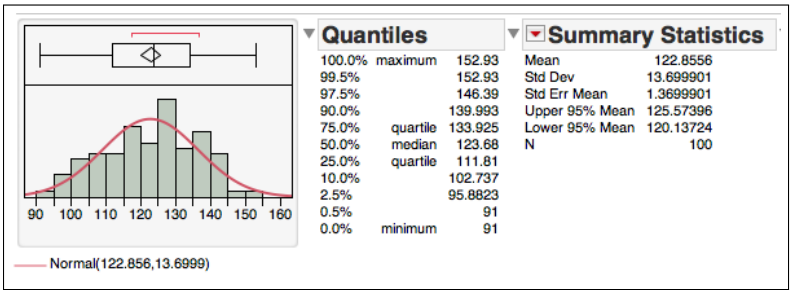


Figure 5.12: Distribution of Mission Time for alternative 3. Note the upper 95^{th} percentile of 120.14 minutes.

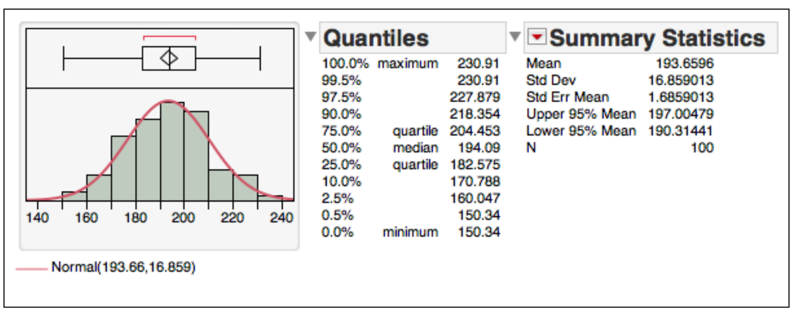


Figure 5.13: Distribution of Mission Time for baseline expanded kill chain model. Note the lower 95^{th} percentile of 190.31 minutes.

With Alternative 3, the mean Mission Time achieved is 122.85 minutes or about 2 hours 3 minutes. This is lower than the mean Mission Time of 193.66 minutes achieved under the baseline expanded kill chain model. As the upper 95^{th} percentile for the third alternative's mean Mission Time is less than the lower 95^{th} percentile of the baseline expanded kill chain model's mean Mission Time, it can be inferred that there is a statistically significant reduction in mean Mission Time using Alternative 3. The results show that Alternative 3 is able to address the previously limiting factor of fighter endurance through the modification

of the sequencing of operational activities for a MUM-T (strike) mission. The use of fuel-efficient flight profiles, such as flying at high altitudes for ingress and egress, by the manned fighters may enable the manned fighters to meet the Mission Time requirements.

5.4 Pugh Method

The Pugh method [36] is a design selection methodology that allows for the comparison of a number of design alternatives against a set of criteria. The Pugh Matrix may also enable the illumination of hybrid alternatives that provides some form of optimization towards the solution.

For this study, the Pugh Matrix is constructed with the criteria as rows, and the baseline expanded kill chain model and three alternatives as columns. The baseline expanded kill chain model is set as the datum that all alternatives are assessed against. The criteria used are described in the following paragraphs.

5.4.1 Criteria Used in Pugh Matrix

The following criteria are used in the Pugh Matrix.

1. **Total Mission Time** – The total time to complete the mission, beginning from the start of aircraft generation to the return of aircraft to the launch platforms.
2. **Mission Time**– The amount of time the assets are required to be airborne for the mission.
3. **RV Time** – The time to complete the formation of the MUM-T (strike) package.
4. **Risk to Assets** – The assessed risk to both air and surface assets as well as the launch platforms. This is a qualitative assessment.

5.4.2 Pugh Matrix Score

Each alternative will be assessed against the baseline CONOPs as described in Section 4.6, and given a score of +1, 0 or -1. A “+1” indicates that the alternative performs better or is more desirable than the datum with respect to the criteria. A “0” indicates that the alternative is on par with the datum with respect to the criteria. A “-1” indicates that the alternative is inferior or less desirable to the datum with respect to the criteria.

5.4.3 Pugh Matrix

Recall that the three alternatives are:

1. Alternative 1 – Aerial refueling tanker support at rendezvous point
2. Alternative 2 – Synchronized launch of manned and unmanned aircraft to achieve "just-in-time" arrival at rendezvous point
3. Alternative 3 – Pre-launch link-up of manned and unmanned aircraft

Table 5.4 shows the Pugh matrix for the baseline CONOPS and the three alternatives. Remarks are included to provide elaboration on the scoring.

Table 5.4: Pugh matrix for baseline and alternatives

Criterion	**Baseline**	**Alt 1**	**Alt 2**	**Alt 3**	Remarks
Total Mission Time	–	0	+1	+1	Alt 2 results in a reduced RV Time and a corresponding reduction in Total Mission Time. Alt 3 results in a reduced Total Mission Time.
Mission time	–	0	0	+1	Alt 3 requires the aircraft to be airborne for the shortest time.
RV Time	–	0	+1	+1	Alt 2 results in a reduction in the RV Time. Alt 3 removes the RV Time from the aircraft airborne time.
Risk to assets	–	-1	0	-1	Alt 1 requires addition assets (tankers and tanker escorts). Alt 3 require that the aircraft carrier and CVEX 2 be in close proximity for pre-launch link-up.
Summary	**–**	**-1**	**+2**	**+2**	

The Pugh matrix shows that Alternative 1 is the least favorable design solution for the refined CONOPS. Not only does it not achieve the desired reduction in Total Mission Time, Mission Time and RV Time, Alternative 1 results in the introduction of addition risks as more assets, including high-value assets (aerial refueling tanker), are required. Alternative 2 does result in a reduction in RV Times, and a corresponding reduction in Total Mission Time. As the communications link-up between the manned and unmanned aircraft is performed between all aircraft prior to aircraft launch, RV Times do not factor into the mission airborne time. Doing so also reduces the Total Mission Time for alternative 3.

The Pugh matrix reveals that both Alternative 2 and Alternative 3 are possible design solutions for CONOPS. However, it should be noted that Alternative 2 did not result in any significant decrease in the Mission Time, which meant that the fighters would still be required to be airborne for an extended period of time. Alternative 3, on the other hand, resulted in a decrease in both the Mission Time and the RV Time. However, Alternative 3 placed the launch platforms at higher risks due to the need for geographical proximity to enable the pre-launch link-up. A possible mitigation will be to employ airborne relays such that both launch platforms can be stationed further apart during the pre-launch link-up. Such a relay capability can potentially be realized with a swarm network of UAVs in operating in a rapidly deployable network (RDN) configuration.

As mentioned in Chapter 2, the USN's recent trials in integrated operations of manned and unmanned aircraft off the aircraft carrier USS Roosevelt (CVN 71) points to a possibility that Alternative 3 may be an feasible CONOPS for the MUM-T (strike) mission. By operating both types of aircraft on the same deck, the link-up can be performed with increased efficiency. Upon link-up, both manned and unmanned can be effectively launched simultaneously.

CHAPTER 6: Conclusions and Future Work

6.1 Conclusion

This study elucidates possible capabilities from the JCA framework that potentially can be performed or realized by the teaming of manned and unmanned aircraft. An initial exploration of such a teaming was performed in the distributed air wing capstone project [16]. It was identified that a potential force multiplier could be in teaming manned and unmanned platforms in operations. Being probably the most complex amongst the various potential capabilities, the manned-unmanned teaming is chosen for further investigation. Specifically, the teaming of manned and unmanned platforms in future strike operations is studied.

This study first developed a design reference mission for a manned-unmanned team conducting a strategic strike mission against surface targets. Key operational activities necessary for the successful conduct of the mission were identified. From these activities, functional analysis is performed to identify the key functions of the mission. This enabled the identification of key processes that would be used in the modeling of the kill chain and expanded kill chain. The kill chain and the expanded kill chain are modeled to enable the study of the factors that affected the efficiency of the kill chains. From these models, the following insights are illuminated.

1. **An accurate target solution is critical** – The study of the F2T2E kill chain model has shown that while the weapon performance such as probability of hit and probability of kill has a direct effect on the mission success rate, the performance of the targeting system has the largest impact. Results presented in Chapter 4, Section 4.5 show that the effect from the "probability of target" factor is twice that of the "probability of kill" and 1.5 times the "probability of hit" factors. A weapon's effectiveness is only as effective as the accuracy of the target information that it is supplied. Of the five processes in the kill chain, four of them, namely, "find, fix, track and target," pertain to the generation of an accurate target solution.

2. **Fighter endurance is a limiting factor in manned-unmanned teaming due to the extended time required for manned-unmanned link-up** – The disproportionate endurance between the fighters and the UCAVs presents a challenge in such teaming operations. The results from the expanded kill chain model suggest that the limiting factor in a MUM-T (Strike) lies in the airborne formation of the MUM-T (Strike) package. Based on simulation of the baseline expanded kill chain simulation model, a minimum Mission Time of 3 hours and 52 minutes is required for the completion of the mission. Current manned fighters cannot achieve such high endurance time without the support of aerial refueling tankers. From the simulation, a significant amount of time is spent by either the fighter or the UCAV holding at the RV point. This is due to the lack of synchronization in the arrival of the assets at the RV point such that efficacy can be achieved in the airborne link up.

Three alternatives are then proposed to either increase the endurance of the fighters or reduce the time needed to perform the link-up. Each alternative is assessed based on their effects on the Mission Time and RV Time. Possible challenges and mitigation are also discussed.

1. **Alternative 1: Tanker support** – The first alternative proposed the use of aerial refueling tanker at the RV point to enable the extension of fighter endurance. This alternative presented several challenges and risks. Challenges were expected in mission planning due to the need for cross-Service coordination between the strike package and the aerial refueling tanker and tanker fighter escorts. In addition, this alternative necessitated the positioning of high value assets within the enemy counter-air radius, which increased the risks involved in the mission. Notwithstanding, it may be possible to employ UCLASS as automated aerial refueling tankers to extend the endurance of manned fighters.
2. **Alternative 2: Synchronization of UCAV launch for "just-in-time" arrivals** – The second alternative proposed the synchronization of manned and unmanned asset launch to minimize the waiting time at the RV point. The alternative assumed that UCAVs will be launched in either one or two waves, with a total of eight UCAVs launched. Analysis of this alternative considered variations in launch time delays as well as variations in the number of UCAVs launched in the first wave. The baseline

model was modified to account for the delay in launch as well as the number of UCAVs launched in each wave. Results from the modeling runs indicate that a delay of 120-minutes and a launch of eight UCAVs in the first wave would serve to reduce the RV Times. However, Mission Time remained largely similar for the fighters. While this alternative is effective in reducing the RV Time, there is the challenge of a near-simultaneous launch of eight UCAVs from a single CVEX 2.

3. **Alternative 3: Pre-launch link-up** – The third alternative proposed that the link-up between the manned and unmanned systems be made prior to the systems taking off from the launch platforms. In this alternative, there was no delay in the launch of the UCAV. A model was developed to study the effects that a pre-launch link-up CONOPS would have on the RV Times and Mission Times. Analysis showed that for this alternative, RV Times was not a significant factor as it did not contribute to the airborne time that was required of the fighters. This was because the link-up was performed prior to the fighters taking off. Analysis of the Mission Time showed a statistically significant reduction in the Mission Time. One challenge of this alternative is the need for both launch platforms to be stationed in closer proximity, thereby increasing the risk to both platforms. A possible mitigation will be to employ airborne relays such that both launch platforms can be stationed further apart during the pre-launch link-up. Such a relay capability can potentially be realized with a swarm network of UAVs in operating in a RDN configuration.

This study has illuminated the potential areas on which efficiency enhancements efforts will need to be focused when considering operations involving manned and unmanned aircraft. Specifically, efficiencies in asset generation and the establishment of data and command links between manned and unmanned aircraft will enhance the operational feasibility of such strike operations. Such operations require close coordination between both manned and unmanned aircraft, and tight integration between the unmanned operators, carrier air wing, aircraft carrier, mission planners and the intelligence community. This study has also illuminated areas in the expanded kill chain of a MUM-T (strike) operation that may impact operational effectiveness, as well as identified possible tactics, concept of operations and future capabilities that will increase the operational tenability of a team of manned and unmanned aircraft for strike operations.

6.2 Future Work

This study took a system engineering approach to investigate a fairly narrow scope of looking at time-efficiency in the expanded kill chain for a manned-unmanned teaming strike operation. Manned and unmanned teaming in operations introduces new frontiers and possibilities in tactics and strategies. Some insights were gained about the factors that impact the kill chain effectiveness. In addition, variations in the asset generation and concept of operations has an effect on the overall kill chain efficiency. However, several areas of improvements in the models and analysis, and new areas of study, have been identified to gain a deeper understanding of the topic of manned and unmanned teaming.

6.2.1 Design Reference Missions

First, this study only focused on one particular capability, that of manned and unmanned teaming. As articulated in Section 2.3, there are a diverse set of capabilities that can potentially be realized by manned and unmanned teaming concepts. Future efforts could be directed towards developing design reference missions for these capabilities. Development of design reference missions will facilitate and enable the illumination of factors, constraints and challenges that should be considered when formulating concept of operations.

For example, the teaming of manned and unmanned aircraft in search and locate operations can possibly increase the rate of area cover. Analysis could focus on the increase in search and location effectiveness if a network of UAVs are teamed with a maritime patrol aircraft. Various search patterns can be evaluated to determine one that is the most effective in area coverage.

Future work may also study the impact of teaming manned and unmanned aircraft in humanitarian aid and disaster relief operations. Amazon, under project Prime Air, is experimenting the use of mini-UAVs to deliver small parcels to their customers [37]. This concept may be extended to the delivery of aid and relief ot inaccessible disaster areas. In the period immediate after a natural disaster, the expeditious delivery of aid and relief to affected areas is of high importance. Using vertical take-off and landing (VTOL) UAVs capable of carrying cargo in an under-slung configuration, the effectiveness and efficiency of aid and relief delivery can be assessed against an operation utilizing only manned aircraft.

6.2.2 Simulation Models

Second, while the models built in this study provide sufficient depth for the objectives of this study, they are not of sufficient fidelity whereby the results could be transferred easily to the operational world. Future effort could build on these models and implement higher fidelity features and parameters so that results can be better validated or verified against real world operations. The parameters used in this study were either obtained from open sources or based on the author's professional experience. Ideally, the parameters used in the models should be realistic to achieve an operationally-accurate model. However, as some of the specifications are classified, proxy or approximate values are used. Nonetheless, the models developed in this study provide a starting point from which modifications can be applied to develop models of higher-fidelity and operational accuracy.

Third, recall that one of the assumptions is that each target is engaged by only one weapon. A missed target is not re-engaged in this study. In reality, targets may be engaged by multiple weapons in multiple passes. This process will likely increase the Mission Time and decrease the mission success rate. Future work can study the impact this has on the mission success rate and the constraints such a CONOPS imposed on the maximum number of targets that can be serviced by a MUM-T strike package.

Fourth, it is also important that the simulation models are verified. No verification of the simulation models against real world operations is done in this study as no similar strike operations exist at present, especially in the area of communications link-up between a manned fighter and unmanned aircraft. However, the advent of U.S. Navy flight trials for integrated operations of manned and unmanned aircraft onboard the aircraft carrier presents opportunities to verify and validate the model.

Fifth, the kill chain for a UAV strike may be more complex than those that were mentioned in this study. For example, while a majority of the processes in the kill chain will likely be automated, humans will likely perform the final process of engagement. In addition, prior to the engagement, there will most likely be a requirement for a human to assess the legitimacy of the target. This additional decision-making process is not modeled in this study, but should be investigated further to better understand the constraints and challenges it might place on the overall kill chain execution. Future efforts may wish to investigate

the threats to the successful engagement of the targets. For example, due to the need for a visual verification of the target prior to weapons release, the video link would be a mission critical system and also a potential single-point of failure. Future researchers could explore alternative links and the requisite bandwidth to ensure that the successful engagement of the target is not compromised due to a failure in the video link.

Sixth, in this study, the triangular distribution is used to model the time required for the performance of asset generation activities as the minimum, maximum and median cycle times for such activities can be intuitively defined. Johnson [38] showed that there was no significant difference in the use of a more intuitively obvious triangular distribution as a proxy for the beta distribution. While cycle time data for asset generation for both the manned fighter and UCAV, in the case of this study, the F-35 Lightning II and X-47B respectively, are unavailable at the time of this study as both aircraft are not operationally fielded at present, estimation of the maximum, minimum and median are made using operational platforms. Future work may wish to consider the use of beta distribution as modeling parameters for the asset generation cycle times.

6.2.3 Future Concepts

Seventh, the study of using UCLASS as aerial refueling tankers for manned fighters as discussed in Section 5.1.1 can be explored. While this still means that additional resources will need to be committed to the operation, the use of unmanned aerial refueling tankers significantly reduces the risk to human lives operating in highly contested airspace. In addition, future work can look into the operational and safety considerations of such a concept. The study into the use of UAVs as aerial refueling platforms may also illuminate any unique design requirements. For example, researchers could explore control system design requirements for UAVs to perform close formation flying.

Eighth, previous examples of manned-unmanned teaming operations involved two or more operators onboard the control platform. In this study, the additional workload to the pilot in having to control two unmanned aircraft is not considered. However, it is reasonable that the workload of the fighter pilot will increase and it is likely that this increase will result in some degradation of the pilot's performance.

6.2.4 Stealth

Ninth, both the manned and unmanned aircraft used in this study are VLO aircraft. Recall that one of the assumptions is that there will be no defensive counter-air launched against the strike package due to the package's stealth capabilities. This stealth capability enables the package to covertly ingress and egress the area of operations whilst avoiding detection by air defense radars. To this end, future research could study the impact and multiplier effects of stealth toward the success of a manned-unmanned teaming. For example, the effectiveness of teaming a non-stealth manned fighter with a stealthy UCAV could be investigated and if such teaming necessitates the development and employment of unique TTPs.

6.2.5 Threats

Lastly, this study assumed that due to the VLO characteristics of the UCAVs and the manned fighters, no enemy defensive counter-air is considered. The UCAVs are able to covertly ingress toward the target and deploy their weapons while avoiding detection. There should be a study of the presence of enemy defensive counter-air and its impact to both the Mission Times and mission success rates.

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Initial Distribution List

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